Cost Benefit Analysis of Passive Treatment Systems

Paul Ziemkiewicz, Jeff Skousen and Jennifer Simmons
National Mine Land Reclamation Center
West Virginia University

INTRODUCTION

Project Objective:

Passive treatment systems have the advantages of a one-time installation cost and, ideally, little to no operation and maintenance cost. However, as emerging technologies, many of these systems are new and experimental. As a result little documentation exists regarding their long term performance, nor their operation and maintenance requirements. By initiating the documentation of these factors, the project was undertaken to quantify the costs and benefits of various types of passive acid mine drainage treatment. These costs were then compared to those of conventional AMD treatment.

Acid Mine Drainage

Acid mine drainage (AMD) is an acidic, iron- and sulfate-rich water that forms under natural conditions when geologic strata containing pyrite are exposed to the atmosphere or oxidizing environments (Skousen 1995). During mining, pyritic material is exposed in great amounts, thereby increasing the likelihood of AMD production and contamination of nearby water resources. AMD can form from both surface and underground coal mining. AMD commonly has a pH of <4.0, iron concentrations of >50 mg/L, sulfate concentrations of >500 mg/L, and various other metals (Al and Mn) in high concentrations.

Alkaline mine drainage is water that has a pH of 6.0 or above, contains more alkalinity than acidity, but may still have dissolved metals that generate acid by oxidation and precipitation. The drainage quality (acid or alkaline) emanating from underground mines or surface mines is dependent on the acid-forming (sulfide) and acid consuming (mainly calcite) minerals contained in the disturbed geologic material. In general, sulfide-rich and carbonate-poor materials are expected to produce acidic drainage. In contrast, alkaline-rich materials, even with significant sulfide concentrations, often produce net alkaline water.

Active and Passive Treatment Systems

Active treatment systems involve treating AMD with alkaline chemicals to raise pH, neutralize acidity, and precipitate metals. Although effective, active treatment is expensive when the cost of equipment, chemicals, and manpower are considered (Skousen et al. 1998). Chemical treatment requires a long-term commitment because the formation of AMD may continue for decades. If AMD problems develop during mining or after reclamation, a plan to treat the discharge must be developed. Treatment of AMD includes neutralization of acidity and precipitation of metal ions to meet the relevant effluent limits. A variety of alternative treatment methods can be employed to meet the limits specified. The high cost and never ending outlook for treatment has caused some operators to forfeit their bonds, leaving the state to deal with the water quality problem.

Over the past 15 years, a variety of passive treatment systems have been developed that do not require continuous chemical inputs and take advantage of naturally occurring chemical and biological processes to improve contaminated mine waters. The primary passive technologies include constructed wetlands, anoxic limestone drains (ALD), vertical flow systems such as successive alkalinity producing systems (SAPS), and open limestone channels (OLC). Some recent additions to this list include limestone and steel slag leach beds. Since the science of passive treatment is young, treatment system designers have little documentation regarding design performance expectations. Most systems are installed as an adjunct to a larger site remediation plan with the intention of achieving some reduction in AMD loadings to receiving streams.

MATERIALS AND METHODS

Sites were chosen from various passive treatment systems throughout Appalachia as part of an ongoing passive treatment evaluation. Information on the design and construction of each system was gathered and water quality data for each site was collected. Some sites had only one type of passive system installed on the site, while most of the sites had a combination of types. Optimally, flows were measured, and water samples were taken and analyzed at the inflow and outflow of each treatment unit. In this way, the amount of acid removed by each component of the system could be estimated. For many sites, however, the data did not permit instantaneous comparisons of incoming and outgoing water from a given treatment unit. Generally, between one and five data points could be used for each treatment unit. This did not permit analysis of performance trends over time. Future monitoring will shed light on this critical parameter.

Specific tasks included:

1) collecting and analyzing the pre-construction and post-construction water quality data from passive treatment systems installed on AMD impacted sites in Pennsylvania, Indiana, Alabama and West Virginia;
2) determining the acidity reductions in the water due to the passive system;
3) and evaluating the cost of treatment based on tons of acid removed per year.

<u>Parameters Used in the Analysis:</u>

Analysis of the data depended on estimating four key parameters: acid load treated, passive treatment unit costs, active treatment costs and service life. The following indicates how they were estimated.

Acid load treated: In some cases it was possible to obtain water samples upstream and downstream of the treatment unit. These data were always used. On other sites, either because of construction methods or sampling strategies, upstream water quality could not be determined when the downstream samples were taken. This would occur, for example, when a treatment unit was built directly on the untreated water source. In these instances, we resorted to pre-construction water quality. This data is clearly of lower reliability. In other cases, we would have, perhaps, ten downstream samples and one upstream sample. In these cases we would only use those data collected on the same date. For many treatment units we had no data on which to base an estimate of acid load treatment. Either there was no upstream sample, no pre-construction data or the downstream sampling combined flows from other treatment units. These units could not be evaluated.

Passive Treatment Unit Costs: Personnel from various state abandoned mine land programs, federal Office of Surface Mining offices, and universities determined the total project cost for each site based on the contractor's costs. These costs usually included the total cost for the site: access, regrading, seeding, fertilization and water management. Items such as access/road construction and transportation are highly specific to the particular site. Rarely was it possible to isolate costs for individual treatment units within a site by using these figures. As the objective was to isolate the treatment cost, we estimated the cost of building the individual treatment units by using a set of standard rates for building passive systems. These rates were $3 per cubic yard for excavation, $25 per ton of limestone, $25 per ton of slag, $70 per ton of calcium hydroxide, $260 per ton of soda ash and $25 per cubic yard of organic matter. Treatment unit dimensions were generally available, therefore, we relied on estimated costs for the cost efficiency evaluations. This provided a constant basis for comparing the cost per ton of acid removed for each treatment unit.

Active Treatment Costs. In order to compare the costs of passive treatment to conventional chemical treatment, we estimated the annual cost of treating a ton of acid load with caustic soda ($NaOH$). This proved to be $430/ton/year (Skousen 1988). This includes only the delivered chemical cost of caustic soda. It does not include equipment, labor, sludge pond construction, cleaning, piping etc. Inclusion of these factors would normally double or triple the cost.

Service Life. Service life is the expected period of performance for a given treatment unit. It was estimated on the basis of the limestone consumption rate. Service life (years) was estimated by dividing the limestone mass by annual acid load treated by 80% (average neutralization potential of limestone). By this process, some units had an estimated service life of only 2 years, while a number of treatment units were removing acid load so slowly that the limestone supply would last for several hundred years. In fact, it is expected that these units will fail by some means long before they run out of limestone. Therefore, we assigned a maximum service of 20 years to all treatment units. Where available, actual service life data supplied by state agencies were used on those sites where unit failure had been determined. Whether the 20 year service life is realistic remains to be seen. Service life can only be verified by continued monitoring.

Data Analysis:

The annual cost of acid load removal ($/ton/year) was estimated for each treatment unit. For those units which gained acid load, this parameter could not be determined since limestone consumption would be zero and service life would be determined as infinite. Controlling service life at 20 years would not solve the problem since tons of acid load treated would also be zero, thus dividing cost by zero. Such estimates would be nonsensical so sites which gained acid load were classified as failures and excluded from further cost/effectiveness analysis.

Success versus failure of an individual treatment unit was determined by two criteria: 1) positive acid treatment, and 2) the system cost of treating AMD was less than that of caustic soda (chemical cost only or $430/ton/year). It is understood that performance estimates are confounded to various degrees by the following factors:

- improper selection/siting: matching a treatment system in the “wrong” type of water
- uncontrolled inflow: undocumented acid or alkaline inflows to the system
- poorly estimated upstream AMD loads: pre-construction data may or may not reflect current inflows

While we made every attempt to control the latter two factors in the data analysis, it was not always possible given the sampling scheme. On the other hand, an error in selection/siting is recorded as a failure of that method. Where such was obvious, we attempted to identify selection/siting problems. Most of these problems will be clarified with improved sampling in future analyses.

SITE DESCRIPTIONS

McCarty Highwall:

The McCarty Highwall is an abandoned surface, and possible underground, mine site located about 10 miles southeast of Bruceton Mills in Preston County, West Virginia. Prior to construction at McCarty, water seeping out along an old spoil pile was flowing into a channel and mixing with a second spoil seep approximately 500 feet downstream. These two seeps form a small stream that flows south into Beaver Creek and eventually into the Cheat River. Along the way, the stream picks up several other small AMD seeps. A 1997 reconnaissance study by the Corps of Engineers showed the first seep was moderately acidic with a pH of 4.1 and a net acidity of 27.5 mg/L. The second seep was similar with a pH of 3.9 and 24.5 mg/L acidity.

Due to the acidity of the on-site AMD sources and the presence of additional acid sources downstream, limestone treatment was insufficient. A stronger alkalinity source was needed -- one that would raise the alkalinity of the on-site water to levels that would neutralize additional AMD entering the stream downstream and one that would last for at least 10 years without maintenance. Earlier studies with steel slag indicated its suitability for such situations.

In October 2000, a series of open limestone channels (OLCs) and steel slag leach beds were installed downstream of seeps 1 and 2. Figure 1 shows the placement of the OLCs and leach beds. All four OLCs were constructed of a limestone sand liner and 6-8" limestone rocks. The leach beds consisted of a settling basin and steel slag check dam. Both check dams were formed from 150 tons of steel slag and rip rapped along the back with 6-8 " limestone rocks. A 200-ft open limestone channel (OLC #1) was constructed from the upper spoil seep to the edge of the first settling basin. A secondary OLC (OLC #1b) was constructed to the left of OLC #1 to carry AMD from an intermittent spoil seep to the first basin. Water leaches from the basin through the center of a steel slag check dam and enters a 300-ft open limestone channel (OLC #2). OLC #2 exits into a limestone gravel area along the edge of the second settlement basin. AMD from the downstream seep flows from the left of basin #2 through a 100-ft open limestone channel (OLC #3) and exits into the gravel area at the edge of the second settling basin. Water enters into settling basin #2 from OLCs #2 and #3 and exits the system through a second steel slag check dam and forms the headwaters of an unnamed tributary of Beaver Creek.

Due to the inability of measuring flow throughout the system and therefore calculating acid loads, the site was evaluated as one treatment unit. The entire site contained 966 tons of steel slag and 302 tons of limestone. The entire cost of the system, including excavation of the limestone channels was $31,970 (Table 1).

Big Bear Lake:

Big Bear Lake is a 35-acre recreational lake located near Hazelton in northeastern Preston County, West Virginia. Although the area was never mined, the lake receives acid water from natural bogs and local, acid-forming rock. This increases acidity and reduces pH of nearby streams, which serve as the headwaters for Big Bear Lake and, subsequently, Beaver Creek.

In 1998, the River of Promise, a local watershed group, approached the owners of Big Bear Lake about the possibility of using passive treatment to neutralize acid in the lake. The management of Big Bear Lake indicated that the lake was dead due to acidity and were interested in developing it into a fishery. So, they agreed to assist in the project. The pH of the lake was about 4, too acid for fish, but since the water entering the lake was of moderate acidity, only 20 mg/L, and contained little to no metals the site was a perfect candidate for limestone treatment (Black et al. 1999).

In the spring of 1999, a 100-ft open limestone channel (OLC) was constructed between the two ponds above the main lake. Figure 2 shows the layout of the treatment area. In addition, a limestone leach bed (LS Bed) was constructed downstream of the swimming pond. The leach bed was constructed using 1500 tons of limestone and receives water from the swimming pond through a pipe. During high flow periods, water also exits the swimming pond through two large culverts, which run underneath the dam road. In September 2000, a second OLC was constructed parallel to the LS Bed to treat this overflow water. A second, smaller limestone leach bed was also constructed in September 2000 above the Top Pond to boast the alkalinity of water entering subsequent systems.

The limestone systems at Big Bear Lake contained 2400 tons of limestone and their estimated total cost was $60,000.

Lick Creek:

The South Fork Patoka River watershed, in southwestern Indiana, has been heavily mined by draglines since the 1940s. Most of the land was not regraded and consists of a series of spoil ridges, furrows, and end cut lakes. Lakes also form in many of the furrow areas and many of these lakes are contaminated with acid mine drainage. Many of the spoil ridges have reforested.

The Lick Creek site consists of two connected mine pits surrounded by acid producing spoil material. Most acidification into the pit lakes result from subsurface flow into the lakes from the spoil. The lakes discharge into a high quality 40-acre wetland created by a beaver dam. From the wetland, the water discharges over the beaver dam and into Lick Creek, which flows into the South Fork of the Patoka River.

Prior to treatment, the lake discharge water quality was pH 2.9 with 350 mg/L acidity, 40 mg/L Fe, 9 mg/L Al, and 45 mg/L Mn. Upon meeting alkalinity in the wetland, the metals immediately precipitated forming a 2-acre delta.

In fall of 1998, an "Aqueous Anoxic Limestone Drain", which is a type of vertical limestone leach bed, was constructed across the lower portion of the lower lake using 4000 tons of limestone rip rap. The drain was constructed as a porous limestone dam across the lake, the upper half of which was sealed off with 60 mil plastic liner to preclude flow through the top portion of the dam where dissolved oxygen levels would cause armoring of the limestone. An 85-ft Open Limestone Channel (OLC) was then constructed in the lake discharge channel using 38 tons of limestone (Figure 3).

The total estimated cost of the OLC was $950 and the estimated cost of the 4000 ton limestone leach bed was $100,000.

Augusta Lake :

The Augusta Coal Field in Pike County, Indiana have been heavily mined by draglines since the 1940s. Visible signs of historic mining, spoil piles and pit lakes, still exist throughout the region. A 1949 study by the Indiana State Board of Health indicated that acid water from coal mining operations in the Augusta Coal Field area was polluting the Patoka River and degrading the water supply for the town of Winslow, Indiana. Augusta Lake was constructed during the fall of 1950 in an effort to reduce the acidity from these mines. The objective was to construct a reservoir large enough to impound sufficient water to dilute the acidity originating in the disturbed surface mine area above, thus reducing the acid load to the Pakota River. Augusta Lake receives acid water from seeps in spoil material throughout its drainage area. Prior to treatment water leaving the lake had a pH of 3.5 and an acidity 310 mg/L.

Efforts to neutralize acidity in the lake, as well as acid seeps entering the lake, began in the summer of 1999 with the dumping of 247 tons of calcium hydroxide directly in Augusta Lake. Recently, treatment has focused on the direct neutralization of AMD at the source. To accomplish this, calcium hydroxide has been dumped into trenches dug into spoil material. The goal is to intercept and neutralize the subsurface flow of acid water which enters the lake. Currently, these alkaline recharge trenches have been installed upstream of the #9 and #8 lake sample points (see Figure 4). To date, a total of 10 tons of soda ash briquettes, 54 tons $Ca(OH)_2$ slurry and 247 tons of solid $Ca(OH)_2$ have been placed within the watershed.

The total estimated cost of the alkaline additions ($Ca(OH)_2$ and soda ash briquettes) to Augusta Lake and its watershed has been $23,732.

Acmar Washer:

This site is located in Acmar, Alabama, approximately 20 miles east of Birmingham. Historic surface mining in the area has left numerous highwall, gob piles and slurry ponds unreclaimed. Prior to reclamation in fall of 2000, acid water leaving the site flowed via a single outlet into Little Black Creek. Water leaving the site had a pH of 3.8, a net acidity of 91 mg/L and Fe, Al and Mn levels of 8.4, 8.1 and 8.9 mg/L.

Much of the water treatment at this site came as a result of surface reclamation. Exposed highwalls were covered and regraded and the slurry ponds were filled in using onsite spoil and gob material. The entire area was regraded, limed and seeded. Limestone channels (total length of 2200 ft, using 2325 tons of limestone) were constructed throughout the area to catch drainage and direct it into a central sediment pond downslope of the reclaimed area. The sediment pond was constructed from a shallow pond with a 1433-ton limestone bed in the middle. The pond has a single outlet: a PVC pipe running from the limestone bed through the dam. The pond was designed so that all water exiting the site would have to leave through the limestone bed.

The OLCs and LS Bed at Acmar contained a total of 3758 tons of limestone and their estimated total cost was $93,950.

Mill Creek:

The Howe Bridge, Filson 1 and McKinley sites are located in the Mill Creek watershed in Jefferson County, Pennsylvania. These sites were selected in an organized effort to remediate AMD impacts to Mill Creek and the Clarion River.

The Howe Bridge system was constructed in 1991 to treat two groundwater seeps. Two ALDs were installed at each seep. Water leaving the ALDs mixes and flows into two sedimentation ponds. Effluent from the second pond discharges into a constructed mushroom compost wetland and on into a Successive Alkaline Producing System (SAPS). The SAPS is composed of 1.5 ft of limestone overlain by 1.5 ft of mushroom compost and 6.2 ft of standing water.

The Filson 1 SAPS was constructed in the summer of 1994 to treat discharge water from an upstream SAPS (Filson 2) that receives AMD from various spoil seeps. The Filson 1 SAPS is 33,869 ft^3 in size and contains 354 yd^3 of limestone overlain by 217 yd^3 of mushroom compost and 4.1 ft of standing water.

Constructed in 1996, the McKinley SAPS has a surface area of 645.6 ft^2. The 19,988-ft^3 SAPS contains 310 ft^3 of limestone overlain by 120 ft^3 of mushroom compost and 1.3 ft of standing water.

The total cost of construction, including excavation, limestone and compost, for the Howe Bridge SAPS was $72,488. The Filson 1 SAPS was estimated at $22,463 and the McKinley SAPS was $16,851.

Moose Creek:

The Sommerville SAPS, in Clearfield County, Pennsylvania was constructed in 1995 on a reclaimed surface mine site to treat AMD flowing from diffuse spoil seeps. The seeps are collected in a ditch and flow into a holding pond before entering the 14520 ft^2 SAPS. The 5.7-ft deep SAPS was constructed with a 1.3 ft limestone base overlain by 1.1 ft of horse manure compost and 3.3 ft of standing water.

The total estimated cost of the Sommerville SAPS was $50,204.

Table 1 shows a summary of the construction dates, materials used and calculated costs for treatment units and systems at each site.

RESULTS

Table 2 contains a glossary of all the abbreviations used in Tables 3-9

The **Acmar Washer** Open Limestone Channel / Limestone Leach Bed system has been very efficient at treating acidity. Table 2 shows that the system has reduced the acid load from 5 tons per year (tpy) to -2 tpy, a reduction of 7.4 tpy of acid. This drop in acidity has reduced the amount of acid leaving the site by 145%. At a cost of $35,825 and an estimated service life of 20 years, it will cost $242 to treat a ton of acid per year at this site (Table 4).

Due to the dissolution rate of $Ca(OH)_2$, **Augusta Lake** will have to receive multiple applications of $Ca(OH)_2$ to treat the acidity in the lake. For this reason, the alkaline additions at Augusta Lake are considered a semi-passive treatment (Caruccio et al. 1984, Ziemkiewicz et al. 1999). Therefore, Augusta Lake was evaluated based on a one year service life.

During 2000, the $Ca(OH)_2$ and soda ash applications to Augusta Lake and its watershed have decreased the acidity in the lake outflow by 70%. At a cost of $23,732, it costs $169 per ton of treatment per year over 20 years.

The **Big Bear Lake** site contains multiple treatment units: two OLCs and two limestone leach beds. Since installation in Sept 2000, Leach Bed 1 has been treating 1.7 tpy of acid at a cost of $408 per ton per year over 20 years. Leach Bed 2 has been doing even better, reducing acid levels by 10.9 tpy at a cost of $31 per ton per year for 11 years. OLCs 1 and 2 have also been reducing acidities to Big Bear Lake (1.7 tpy and 2.8 tpy, respectively). In fact, OLC 2 has been effective at reducing 100% of the acid entering its channel.

The **McCarty Highwall** treatment system consists of three open limestone channels to collect and transport acid water to two steel slag leach beds. Due to the nature of the channels and beds, flow could only be measured at the discharge of the entire system. In addition, due to the dissolution characteristics of the slag, there has been a constant reduction in the amount of alkalinity being leached out of the beds. At the last sampling, the leach beds were generating 14.7 (Leach Bed 1) and 37 (Leach Bed 2) mg/L of alkalinity. It is believed that the beds will continue to perform at this level and that using average data from the last 4 months would greatly overestimate the alkalinity that the system will generate over its 20-year service life. Therefore, the McCarty system was evaluated based on its most current water quality analysis.

Compared to pre-construction water quality, the system has treated 19 tpy of acid and reduced acidity by 181%. At a total cost of $31,970, the system costs $84 per ton per year for 20 years.

The **Mill Creek** SAPS have all effectively reduced acidities. The Howe Bridge SAPS (SAPS 1) treated 13 tpy of acidity at a cost of $279 per ton per year for 20 years. The Filton 1 and McKinley SAPS both reduced acid loads by approximately 4.5 tpy at a cost of $239 per ton per year for 20 years and $179 per ton per year for 20 years, respectively.

The **Moose Creek** Sommerville SAPS treated 8.9 tpy of acid at $282 per ton per year for 20 years.

Treatment at the **Lick Creek** site is primarily a Limestone Leach Bed, which was constructed as a limestone dam in the middle of a pit lake. The leach bed treats 47.1 tpy of acid and the water loses another 13.2 tpy of acid as it passes through limestone in the discharge channel. The systems at Lick Creek are some of the most cost efficient in this study. The limestone bed costs only $106 per year for 20 years to treat a ton of acid and the OLC, whose service life was calculated at 2.3 years, is the most cost efficient at $31 per ton per year for 2.3 years.

SUMMARY AND CONCLUSIONS

A total of 13 passive treatment systems on 7 remediation sites were evaluated. Where possible, the effect of each treatment unit or system was evaluated by comparing acid loads entering and exiting it. In instances where inflow water quality was missing or unattainable, pre-construction water quality was used as inflow.

Table 4 lists all treatment units that reduced acid load (positive treatment effect). Tables 5-7 rank the treatment units according to unit cost over service life, treatment cost relative to chemical treatment cost, acid load treated and cost. Table 8 shows the performance of treatment units of a given treatment technology and Table 9 summarizes the success rate of various methods.

According to the water quality data, all treatment systems in this study had a positive treatment effect and reduced varying amounts of acidity (Table 6). The semi-passive alkaline additions at Augusta Lake seem to be treating the most acidity of all the systems at 140.4 tpy. Of the passive systems, the limestone leach bed at Lick Creek is reducing the acid load by 47.1 tpy.

To be considered a successful treatment, the system also had to treat acidity cheaper than caustic soda, which cost $430 per ton of acid per year. All 13 systems in this evaluation were cheaper than caustic, costing from $31/ton/yr over service life at the Big Bear Lake LS Bed 2 and the OLC at Lick Creek to $408/ton/yr over service life for the LS Bed 1 at Big Bear Lake. Therefore, 100% of the systems in this evaluation treated acid successfully.

Due to the limited size of this study, the alkaline addition at Augusta Lake and the Slag Beds/OLCs at McMarty Highwall were only evaluated for one unit or system. However, those with multiple units, such as OLCs, LS Beds and SAPSs, show that even similar systems have variable treatment success. For example, all the OLCs in this study treated acid successfully. However, the OLC at Lick Creek treated 10 tpy more of acid and had a unit cost over service life of more than $170 cheaper than the OLCs at Big Bear Lake. Additionally, although the limestone bed at Lick Creek treated more acid load than the beds at Big Bear Lake, Limestone Bed 1 treated acid the cheapest at $31 per ton per year for twenty years.

The SAPS treated 7.8 tpy at $245 per ton per year. Interestingly, they all treated various amounts of acid but, because of their construction costs, had similar unit cost over a 20-year service life.

Of the systems evaluated in this study, the Slag Beds/ OLCs system at McCarty Highwall was the most efficient in terms of average unit cost at $84 per ton per year. The OLCs were the next most efficient, treating an average of 4.4 tpy at an average unit cost of $164. The alkaline addition at Augusta Lake was a close third, treating 140.1 tpy at a unit cost of $169. The four Limestone Beds treated an average of 17.5 tpy at an average unit cost of $198 per ton per year.

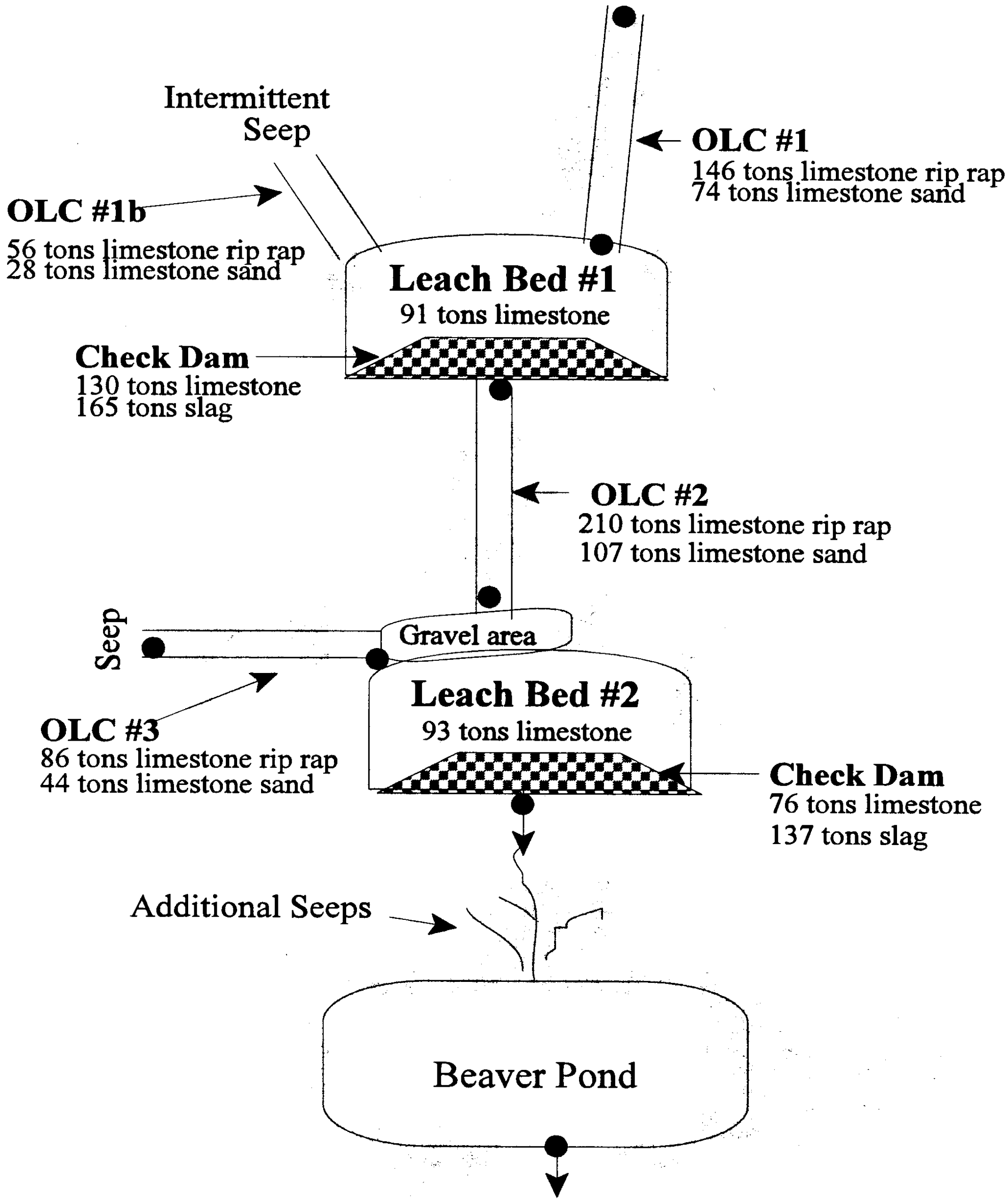

Figure 1: McCarty Highwall Treatment area.
Black dots mark the sample stations.

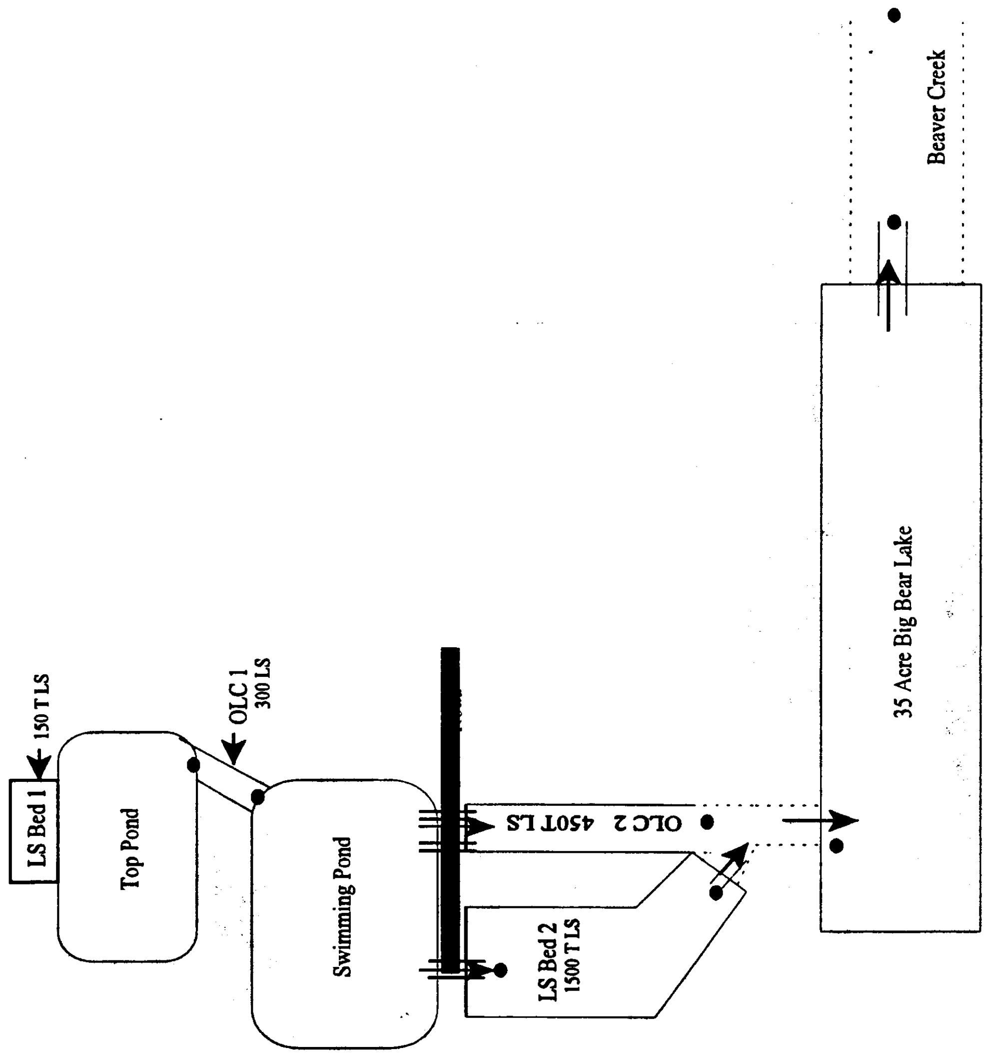

Figure 2: Diagram of Big Bear Lake Treatment Area
Arrows trace flow of water in system and dots mark sampling points.

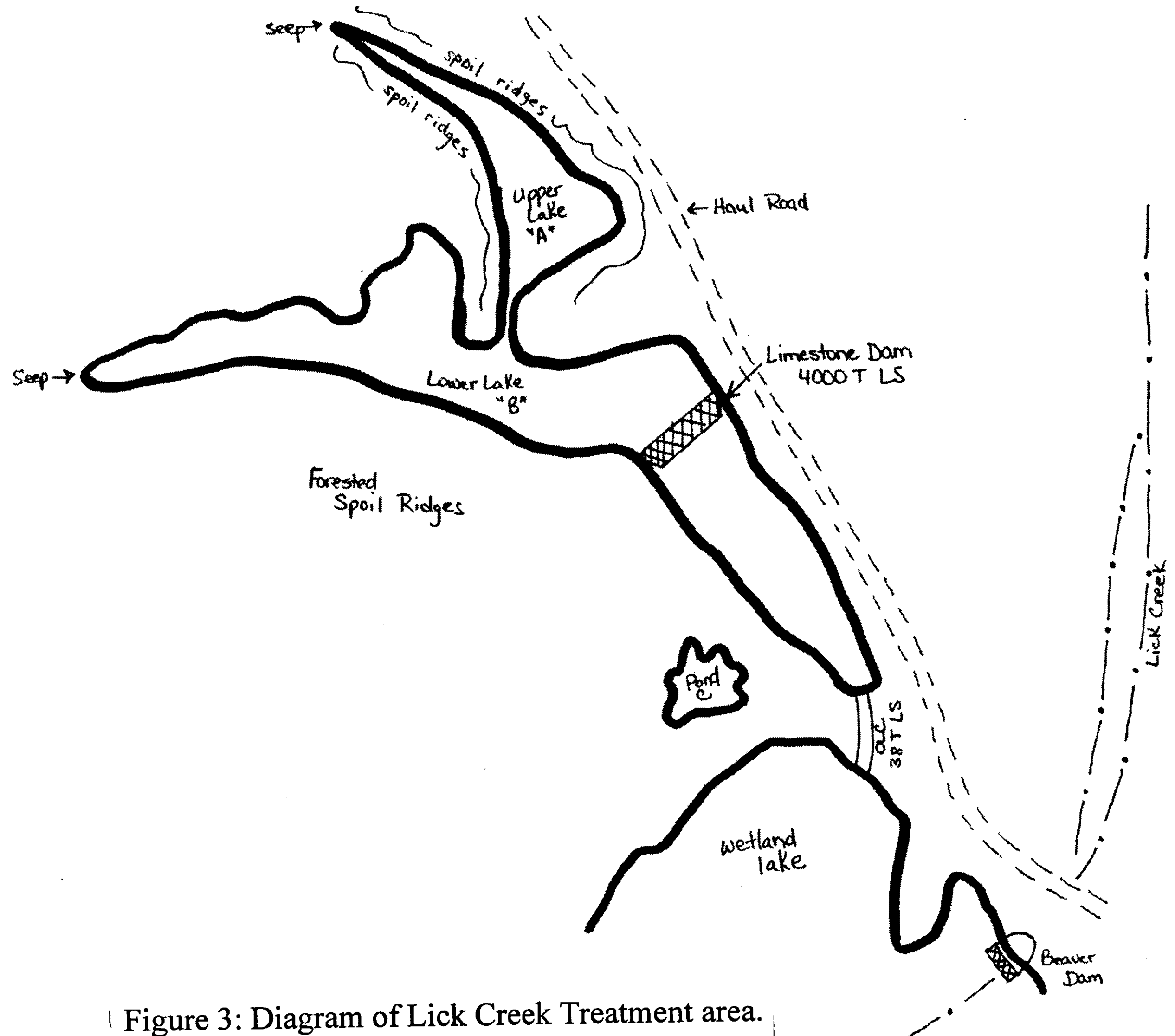

Figure 3: Diagram of Lick Creek Treatment area.

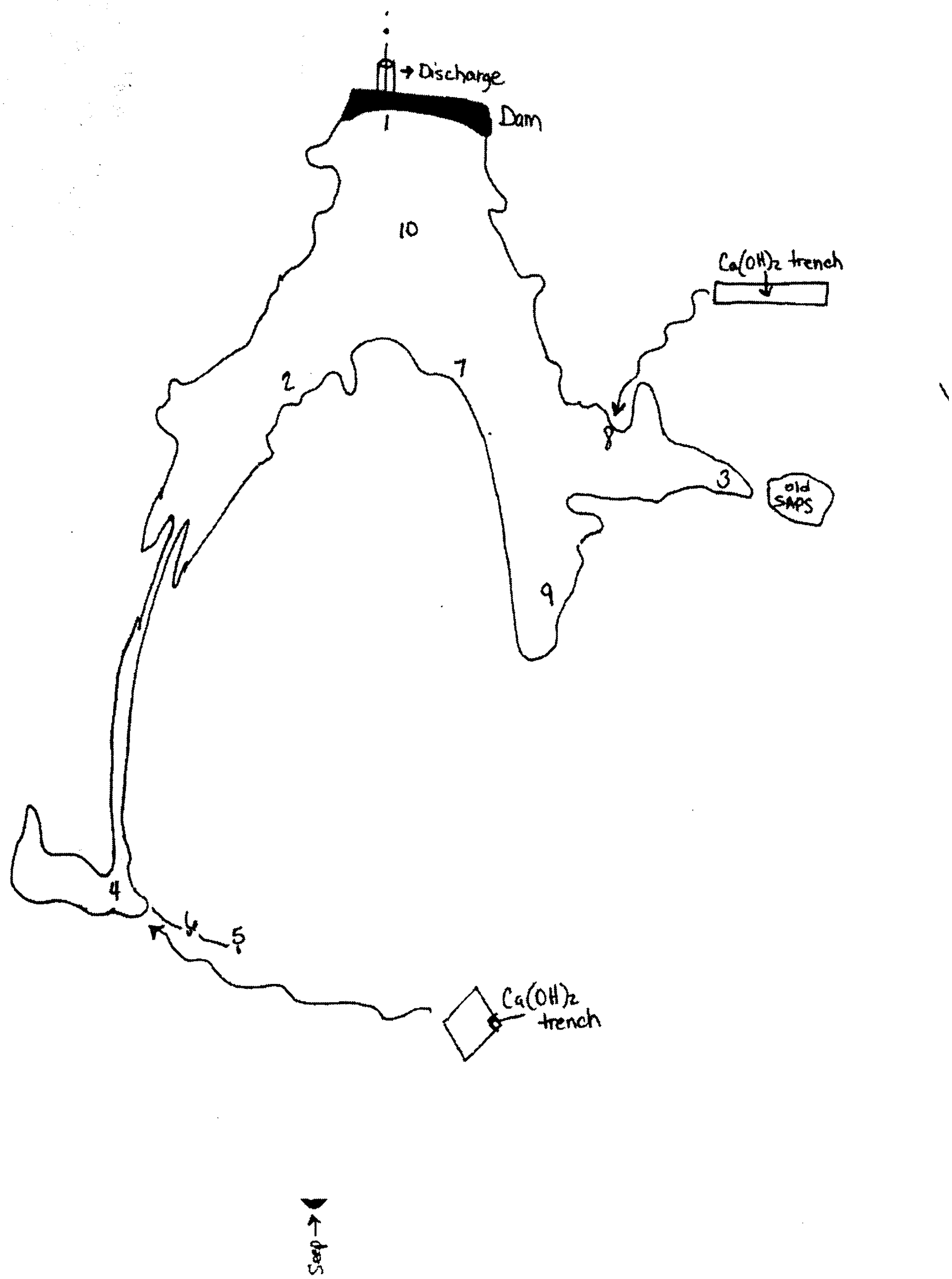

Figure 4: Diagram of Augusta Lake. Sample points are numbered and wavy arrows represent approximate flow of alkaline water from trenches.

Table 1: Summary of sites evaluated in this study. Table shows constructed date, amounts of materials used and calculated costs.

Site	Treatment	Construction Date	Excavated (yd3)	Limestone (tons)	Slag (tons)	Compost (yd3)	Soda Ash/ Ca(OH)2 (tons)	Cost
Acmar Washer	LSB	Fall 2000		1433				$35,825
Augusta Lake	Alk addition	2000					312	$23,732
Big Bear Lake	OLC 1	Sept 2000		300				$7,500
	OLC 2	Spring 1998		450				$11,250
	LSB 1	Sept 2000		150				$3,750
	LSB 2	Spring 1998		1500				$37,500
Lick Creek	LSB	Fall 1998		4000				$100,000
	OLC	Fall 1998		38				$950
McCarty Highwall	SLBs/OLCs	Oct 2000	90	966	302			$31,970
Mills Creek	SAPS 1	Nov 1991	5496	1344		896		$72,488
	SAPS 2	Summer 94	1254.4	531		217		$22,463
	SAPS 3	Fall 1996	740.3	465.8		119.4		$16,851
Moose Creek	SAPS 4	Summer 95	3065.4	1048.7		591.6		$50,204

Table 3. AMD treatment sites evaluated in this project. The table compares pre and post treatment ave flows and acidity. It also includes average acid loads. Acid load values represent the average calculated for each sampling date.

			pre-treatment			post-treatment			acid load	
	treatment	treat.	flow	acidity	acid loa	flow	acidity	acid load	treated	acid load
Site	technology	unit. #	gpm	mg/L	tpy	gpm	mg/L	tpy	(t/yr)	% chang
Acmar Washer	LSB	1	25	92	5	25	-42	-2	7	-145%
Augusta Lake	Alk addition	1	292	310	199	744	35	59	140	-70%
Big Bear Lake	OLC	1	667	19	16	667	10	14	2	-11%
	OLC	2	158	8	3	158	2	0	3	-100%
	LSB	2	587	19	21	746	10	10	11	-52%
	LSB	1	188	8	4	188	-7	-1	5	-131%
		Total:	1600	55	43	1759	14	23	20	
Lick Creek	LSB	1	75	515	85	75	230	38	47	-55%
	OLC	1	75	230	38	75	150	25	13	-35%
		Total:	150	745	123	150	380	63		
McCarty Highw	SLBs/OLCs	1	104	46	11	104	-37	-9	19	-181%
Mill Creek	SAPS	1	42	296	27	42	153	14	13	-49%
	SAPS	2	32	247	17	32	166	13	5	-27%
	SAPS	3	27	52	2	27	-49	-2	5	-209%
		Total:	102	595	46	102	270	24	22	
Moose Creek	SAPS	1	46	347	30	46	220	21	9	-29%

Table 2: Glossary of abbreviations used in data table.

Abbreviation	Treatment
Alk addition	Addition of $Ca(OH)_2$ and Soda Ash briquettes
LSB	Limestone Leach Bed
OLC	Open Limestone Channel
SAPS	Successive Alkaline Producing System
SLBs/OLCs	Slag Leach Bed and Open Limestone Channel System

Table 4. AMD treatment units which accomplished acid load reductions. Service life was estimated using 2(for non limestone systems. Limestone system life was estimated by the formula: LS tons x 0.8/ac treated per year. For purposes of this study, 20 years was assumed to be the maximum life for any Treatment unit costs are based on dimensions and material volumes.

Treatment	Site	Unit. #	pH of incoming water	years in service	treatment unit cost	acid load treated (t/yr)	est. service life (yrs)	unit cost over service life ($/t/yr)
Alk addition	Augusta Lake	1	3.5	1	$23,732	140.4	1	$169
LSB	Acmar Washer	1	3.8	0.5	$35,825	7.4	20	$242
LSB	Lick Creek	1	2.7	2	$100,000	47.1	20	$106
LSB	Big Bear Lake	2	5.7	3	$3,750	10.9	11	$31
LSB	Big Bear Lake	1	5.6	0.5	$37,500	4.6	20	$408
OLC	Big Bear Lake	1	5.0	3	$7,500	1.7	20	$221
OLC	Big Bear Lake	2	5.6	0.5	$11,250	2.8	20	$201
OLC	Lick Creek	1	4.8	2	$950	13.2	2.3	$31
SAPS	Mill Creek	1	5.3	6	$72,488	13.0	20	$279
SAPS	Mill Creek	2	3.7	3	$22,463	4.7	20	$239
SAPS	Mill Creek	3	4.2	1	$16,851	4.7	20	$179
SAPS	Moose Creek	4	3.5	2	$50,204	8.9	20	$282
SLBs/OLCs	McCarty Highwall	1	3.7	0.5	$31,970	19.0	20	$84
Totals:	13				$414,483	278.4		$2,472

Table 5. Treatment units ranked according to unit cost over service life compared with treatment of same ac with caustic Treatment unit costs are based on dimensions and material volumes. A cost benefit o caustic is anything that is less than $430 per ton per year over the service life.

Treatment	Site	Unit. #	pH of incoming water	years in service	treatment unit cost	acid load treated (t/yr)	est. service life (yrs)	unit cost over service life ($/t/yr)
LSB	Big Bear Lake	2	5.7	3	$3,750	10.9	11	$31
OLC	Lick Creek	1	4.8	2	$950	13.2	2.3	$31
SLBs/OLCs	McCarty Highwall	1	3.7	0.5	$31,970	19.0	20	$84
LSB	Lick Creek	1	2.7	2	$100,000	47.1	20	$106
Alk addition	Augusta Lake	1	3.5	1	$23,732	140.4	1	$169
SAPS	Mill Creek	3	4.2	1	$16,851	4.7	20	$179
OLC	Big Bear Lake	2	5.6	0.5	$11,250	2.8	20	$201
OLC	Big Bear Lake	1	5.0	3	$7,500	1.7	20	$221
SAPS	Mill Creek	2	3.7	3	$22,463	4.7	20	$239
LSB	Acmar Washer	1	3.8	0.5	$35,825	7.4	20	$242
SAPS	Mill Creek	1	5.3	6	$72,488	13.0	20	$279
SAPS	Moose Creek	4	3.5	2	$50,204	8.9	20	$282
LSB	Big Bear Lake	1	5.6	0.5	$37,500	4.6	20	$408
Totals:	13				$414,483	278.4		$2,472

Table 6. Treatment unit costs ranked according to acid treated per year. Treatment unit costs are dimensions and material volumes.

Treatment	Site	Unit. #	pH of incomin water	years in service	treatme unit cos	acid loa treated (t/yr)	est. servic life (yrs)	unit cost ov service life ($/t/yr)
OLC	Big Bear Lake	1	5.0	3	$7,50	1.7	20	$22
OLC	Big Bear Lake	2	5.6	0.5	$11,25	2.8	20	$20
LSB	Big Bear Lake	1	5.6	0.5	$37,50	4.6	20	$40
SAPS	Mill Creek	3	4.2	1	$16,85	4.7	20	$17
SAPS	Mill Creek	2	3.7	3	$22,46	4.7	20	$23
LSB	Acmar Washer	1	3.8	0.5	$35,82	7.4	20	$24
SAPS	Moose Creek	4	3.5	2	$50,20	8.9	20	$28
LSB	Big Bear Lake	2	5.7	3	$3,75	10.	11	$3
SAPS	Mill Creek	1	5.3	6	$72,48	13.	20	$27
OLC	Lick Creek	1	4.8	2	$95	13.	2.3	$3
SLBs/OLCs	McCarty Highw	1	3.7	0.5	$31,97	19.	20	$8
LSB	Lick Creek	1	2.7	2	$100,00	47.	20	$10
Alk addition	Augusta Lake	1	3.5	1	$23,73	140.	1	$16
Totals:	13				$414,48	278.		$2,47

Table 7. Treatment unit costs ranked according to total project cost. Treatment unit costs are based on dimensions and material volumes.

Treatment	Site	Unit. #	pH of incoming water	years in service	treatment unit cost	acid load treated (t/yr)	est. service life (yrs)	unit cost over service life ($/t/yr)
OLC	Lick Creek	1	4.8	2	$950	13.2	2.3	$31
LSB	Big Bear Lake	2	5.7	3	$3,750	10.9	11	$31
OLC	Big Bear Lake	1	5.0	3	$7,500	1.7	20	$221
OLC	Big Bear Lake	2	5.6	0.5	$11,250	2.8	20	$201
SAPS	Mill Creek	3	4.2	1	$16,851	4.7	20	$179
SAPS	Mill Creek	2	3.7	3	$22,463	4.7	20	$239
Alk addition	Augusta Lake	1	3.5	1	$23,732	140.4	1	$169
SLBs/OLCs	Mccarty Highwall	1	3.7	0.5	$31,970	19.0	20	$84
LSB	Big Bear Lake	1	5.6	0.5	$37,500	4.6	20	$408
SAPS	Moose Creek	4	3.5	2	$50,204	8.9	20	$282
SAPS	Mill Creek	1	5.3	6	$72,488	13.0	20	$279
LSB	Acmar Washer	1	3.8	0.5	$35,825	7.4	20	$242
LSB	Lick Creek	1	2.7	2	$100,000	47.1	20	$106
Totals:	13				$414,483	278.4		$2,472
LSB	Big Bear Lake	1	5.6	0.5	$37,500	4.6	20	$408
Totals:	13				$414,48	278.4		$2,472

Table 8.	Performance of individual treatments within treatment technologies. Treatment unit costs dimensions and material volumes.								
count	treatment technolog	Site	Unit. #	pH of incomin water	years in service	treatmen unit cost	acid loa treated (t/yr)	est. servic life (yrs)	unit cost ove service life ($/t/yr)
1	Alk additio	Augusta Lake	1	3.5	1	$23,73	140.	1	$16
1	LSB	Lick Creek	1	2.7	2	$100,00	47.1	20	$10
2	LSB	Acmar Washer	1	3.8	0.5	$35,82	7.3	20	$24
3	LSB	Big Bear Lake	1	5.7	3	$3,75	10.9	11	$31
4	LSB	Big Bear Lake	2	5.6	0.5	$37,50	4.6	20	$40
	avg.					$44,26	17.5		$19
1	OLC	Big Bear Lake	1	5.0	3	$7,50	1.7	20	$22
2	OLC	Big Bear Lake	2	5.6	0.5	$11,25	2.8	20	$20
3	OLC	Lick Creek	1	4.8	2	$95	13.2	2.3	$31
	avg.					$6,56	4.4		$15
1	SAPS	Mill Creek	1	5.3	6	$72,48	13.0	20	$27
2	SAPS	Mill Creek	2	3.7	3	$22,46	4.7	20	$23
3	SAPS	Mill Creek	3	4.2	1	$16,85	4.7	20	$17
4	SAPS	Moose Creek	4	3.5	2	$50,20	8.9	20	$28
	avg.					$40,50	7.8		$24
1	SLBs/OLC	McCarty Highw	1	3.7	0.5	$31,97	19.0	20	$84

Table: 9.	Summary of technologies, their average costs and success rates. Successful applications were those which treated acid and did so at a rate less than the chemical cost of caustic soda ($430/ton of acid load).					
treatment technology	number of units	average unit cost	average unit cost ($/t/yr)	average acid treated (tpy)	success	failure	success ratio
Alk addition	1	$23,732	$169	140.1	1	0	100%
LSB	4	$44,269	$198	17.5	4	0	100%
OLC	3	$6,567	$151	4.4	3	0	100%
SAPS	4	$40,502	$245	7.8	4	0	100%
SLBs/OLCs	1	$31,970	$84	19	1	0	100%
Totals:	13				13	0	100%

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