THE EFFECTIVENESS OF ACID ROCK DRAINAGE CONTROL STRATEGIES AT THE SUMMITVILLE MINE[1]

V.L. Ketellapper and J.W. Christiansen[2]

Abstract. The Summitville Mine, located in Southwestern Colorado, is an abandoned open pit and underground gold mine. During recent open pit mining, the volume of acidic metal laden water released from the site significantly increased. This was attributed to development of the mine pits, development of the waste rock piles, and increased discharges from the drainage adit. The release of acid rock drainage from the site resulted in the destruction of the aquatic ecosystem for more than twenty miles downstream. Beginning in 1993, plans were implemented to reduce the amount of acid rock drainage from the mine. The goal of these activities is to reduce the need for long term treatment to control metals released from the site. The majority of this stabilization work has been completed. The work implemented includes extensive removal of waste rock and tailings, backfilling and capping of the mine pits, and plugging of two drainage adits. In the interim, chemical treatment is being utilized to reduce metal loading. The remaining phases of site stabilization work, including reclamation of the mine site, are planned to be completed in 2000. This study discusses actions taken to reduce the amount of acid rock drainage generated and released from the Summitville Mine, the cost of these actions, and the corresponding reduction in metal loading. Copper loading is analyzed as an indicator of the effectiveness of the actions taken to control acid rock drainage. The monitoring of copper at the downstream compliance point indicates an overall seventy percent reduction in metal loads released from the site. Reclamation is predicted to reduce the loads such that little or no water treatment will be necessary to meet water quality goals.

Additional Key Words: reclamation

Introduction

The Summitville Mine, located in Southwestern Colorado, is an abandoned open pit gold mine. The site was operated as an underground gold mine and more recently as a large tonnage open pit heap leach gold mine. The mine is located at an average elevation of 11,500 feet in a mountainous area of very heavy snowfall. The disturbed portion of the site encompasses some 550 acres. A map of the site showing key features is shown in Figure 1.

Historic mining led to a network of underground workings and a relatively small amount of acid generating tailings being deposited around the site. During this period, water quality downstream was not substantially degraded. After open pit mining commenced in the mid-1980's, the volume of acidic metal laden water released from the site significantly increased. This was attributed to the development of the mine pits above the remaining underground workings and the deposition of extensive waste rock piles around the site. The release of the acid rock drainage resulted in the destruction of the aquatic ecosystem for more than twenty miles downstream of the mine.

The water quality of the mine was characterized by low pH (often below three) and elevated metals content. Water discharging from the primary drainage adit, the Reynolds, was often supersaturated with copper, showing concentrations above 300 ppm. The primary metals of concern were iron, manganese, and copper, though most metals showed elevated concentrations. Because of its high concentrations, toxicity, and uniqueness to the site, copper was chosen as the indicator metal. The remainder of the watershed does not naturally exhibit elevated copper concentrations (though it does show highly elevated amounts of other metals), so the effects of the mine on downstream areas are readily examined through the monitoring of copper. Other metals of concern respond similarly to copper in the acidic environments found at the site (MK, 1997).

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2. Victor L. Ketellapper is a remedial project manager, James W. Christiansen is an engineer, U.S. Environmental Protection Agency, Region 8, Denver, Colorado, 80303.

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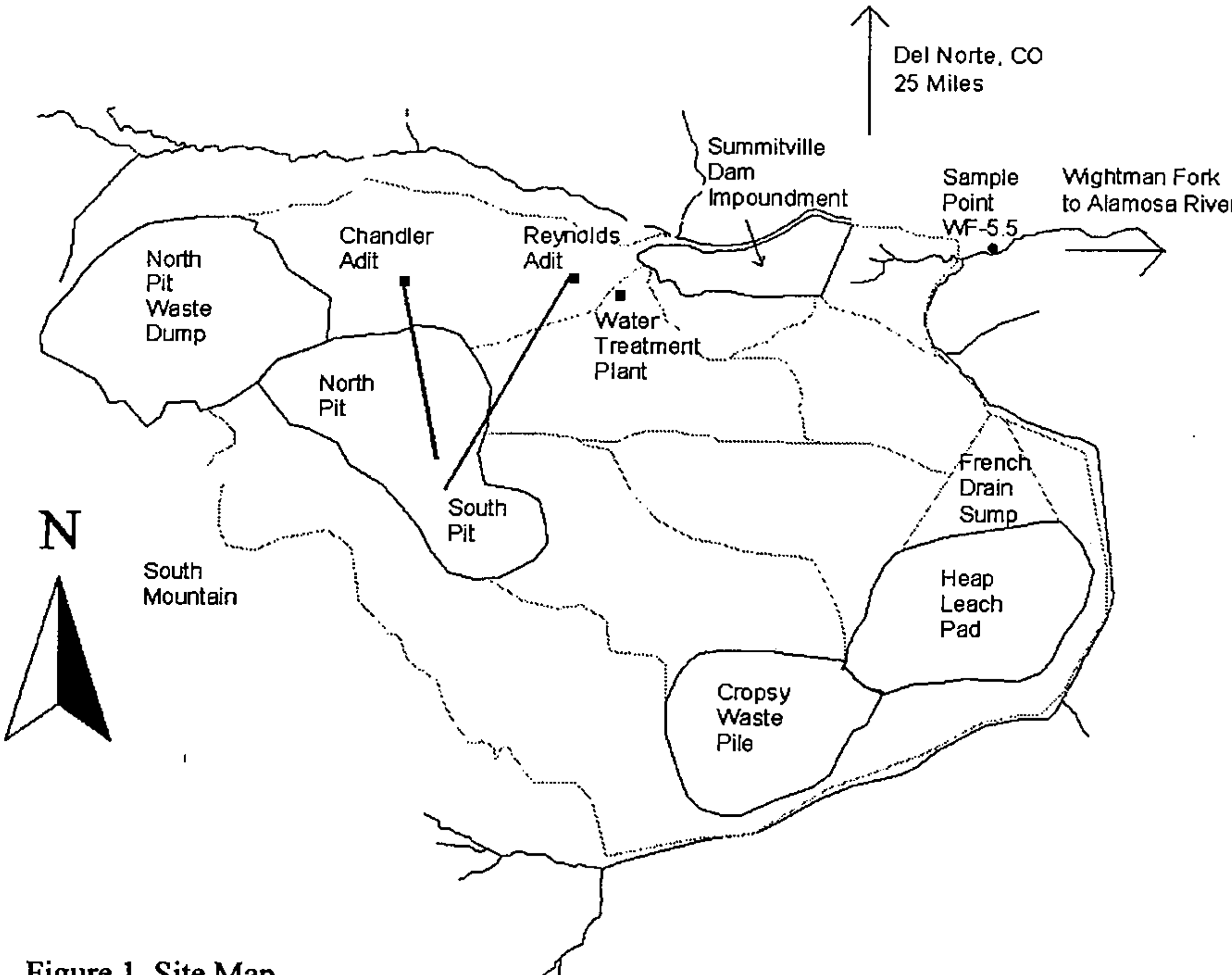


Figure 1. Site Map.

Beginning in 1993, plans were implemented to reduce the amount of acid rock drainage from the mine. The goal of these activities is to reduce the need for long term water treatment.

Water Treatment

Water treatment began by the mine operators during the early 1990's was continued and improved after the site was abandoned in 1992. The first concern was to draw down water levels within the heap leach pad (HLP), which was in danger of overtopping the containment dikes. If the dikes were breached, a massive release of cyanide and heavy metal laden water would have occurred. When water levels reached safe measurements, discharges from the treatment plants were rerouted back to the HLP to flush the ore of cyanide. Three sources of acid rock drainage (Reynold's Adit, Cropsy Waste Pile, and the French Drain Sump) were also tapped for treatment through alkaline precipitation. Only one new treatment facility was constructed; three others were converted from existing facilities. At peak, the four facilities were treating acid drainage and heap leachate at over 800 gallons per minute (GPM). After February 1996, all sources of acid drainage on the mountain were captured in a containment reservoir and routed for treatment at one central facility. This central facility was modified to treat 900 GPM effectively and is operating at a cost of 2.2 million dollars per year. The total cost of water treatment to date is approximately 65 million dollars.

Source Removal/Pit Capping

During the period 1993-96, the majority of the Beaver Mud Dump, Cropsy Waste Pile, and Cleveland Cliffs Tailings Pond were excavated and backfilled into the mine pits. Prior to placement of the mining waste into the pits, a clay liner was installed. Two feet of lime was placed on top of the clay liner to neutralize any acid water generated during the filling of the mine pits. In 1995, the area around the tailings pond was excavated further and improved to become the Summitville Dam Impoundment (SDI), which serves as a catchment for the majority of flows generated on-site and has a capacity of 90 million gallons. In all, some 4.8 million cubic yards of acid generating waste was removed and backfilled. The south pit was capped with a geosynthetic clay liner (GCL) in 1995; the north pit backfill is ongoing, though it is free draining. A clay cap is planned for the north pit. These actions were conducted to remove acid generating rock from saturated areas, to provide backfill for the excavated pits, and to reduce infiltration into the mine pool. The total cost for these actions was 32 million dollars.

Adit Plugging

In order to slow the discharge of acid rock drainage from the underground mine workings, the Reynolds and Chandler Adits were plugged in early 1994. The Chandler plug failed soon after, but was repaired by late 1994. The eventual goal is to restore the South Mountain water table to pre-mining levels, render much of the mine pool anoxic, and halt the oxidation process. The total cost expended on adit plugging was approximately 1.7 million dollars.

Recontouring/Reclamation

Extensive recontouring has been implemented at the site. Drainages have been rerouted to provide maximum catchment in sediment ponds and the SDI, reduce erosion, and eliminate ponding in the most acid generating areas. Sediment ponds, drainage ditches, and pipes require constant maintenance. The HLP was recontoured and is currently being capped with GCL. Reclamation consisting of erosion control devices, liming, stockpiled topsoil replacement, soil amendments, and seeding is planned for approximately 500 acres of the site and is scheduled for completion in 2001. Further reclamation is considered necessary to reduce erosion, to reduce infiltration into the mine pool, and to decrease acid rock drainage generated by the site. The cost of recontouring and capping the HLP was 15 million dollars. The cost to complete the reclamation at the site is approximately 30 million dollars.

Methods

Data

Surface water quality sampling for the site began in earnest in 1993 when the Total Maximum Daily Load Program (TMDL) was initiated. Samples were collected on a regular basis (monthly or weekly) at over 100 locations around the site in order to accurately characterize the acid rock drainage problem. Over 2600 samples have been collected to date. With minor exceptions, the only data gaps for critical sample points after 1993 were the result of inaccessibility in winter conditions, though some points were sampled sporadically. The downstream point of compliance, known as sampling point WF-5.5 and shown in Figure 1, was sampled consistently on a weekly basis throughout this period. The average number of samples analyzed for WF-5.5 in a given year was approximately forty. Data from WF-5.5 are used in this report to quantify the total copper loading being generated by the site.

Data used in this study are somewhat "raw". Though various quality control procedures were used by the analyzing lab, only limited statistical data validation was performed. Due to the complexity and uncertainty inherent to the site, further validation was not considered.

Loading Generated by the Site

Copper loading in units of pounds per day, calculated as the product of total recoverable copper concentration, flow, and a conversion factor, was used to quantify the acid rock drainage problem. To find the yearly average copper load reporting (post-treatment) to WF-5.5, the load for each sample date was first calculated. Next, an average for each month was obtained and the months were averaged over a year. Unsampled months were interpolated assuming a normal distribution. To compensate for water treatment activities upstream of WF-5.5, the average copper load removed (also in lbs/day) for each year was calculated and added to the loads reporting to WF-5.5. In this way, an accurate picture of loads generated by the site (pre-treatment) can also be presented.

Peak loads generated by point sources were also examined to "validate" the observations at WF-5.5. Because a large percentage of loading occurs during high runoff, it is beneficial to examine how high the peak concentrations rise in a given year. Also, sampling upstream of water storage and treatment eliminates any bias these activities may cause. This analysis was performed by summing the four highest single day readings for different point sources in a given year.

Yearly precipitation amounts were considered qualitatively. Because loading is directly proportional to flow, high and low runoff years directly affected loading values, regardless of copper concentration.

Load Reductions

Pre-treatment load reduction for the site (i.e. source attenuation) observed from 1993 to 1996/97 was found by substracting the current average load at WF-5.5 in lbs/day from the initial load. Because 1993 was an exceptionally high loading year, the initial load was taken conservatively as three quarters of the 1993 average. The current load was taken as the average of 1996 loads (a very dry year) and 1997 loads (a very wet year). These steps together prevented gross misstatement of reductions achieved. Similar calculations were performed for peak point source loads.

To determine the source of the load reductions, a somewhat qualitative approach was used. Reductions in load were considered achievable through two mechanisms: reduction in flow rates or reduction in concentrations. To analyze current reductions in flow, it was assumed the amount of water leaving the site is fixed by precipitation and that only the **ratio** of water leaving via surface runoff to that infiltrating and leaving via groundwater discharge can be changed. Water leaving via surface runoff has less water-rock contact time and is far less contaminated. Therefore, a one fold reduction in infiltration (a higher surface to groundwater ratio) was assumed to produce a similar reduction in loading. Infiltration rates were not calculated directly but were inferred from observations of peak groundwater level rises in wells which showed strong connections to the mine pool. Again, the relationship was assumed to be 1:1, meaning a 50% reduction in peak water level rise was the result of a 50% reduction in infiltration. Predicted load reductions due to future actions are discussed in more detail in the next section.

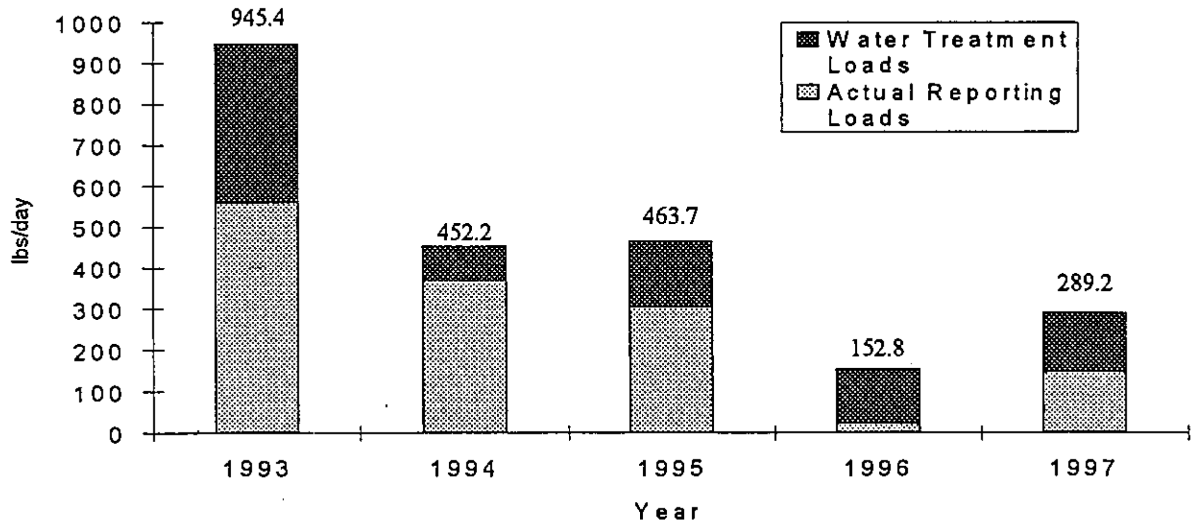
Results

Average copper loading at the compliance point, WF-5.5, is shown in Figure 2. Peak loads for point sources are shown in Figure 3. The data indicate pre-treatment loads generated by the site have declined significantly from 1993 levels. Both average and peak loads show the same pattern of decline. 1997 values, though higher than 1996, showed a continued trend of improvement from previous years. This was in spite of the highest yearly precipitation observed since the onset of remediation . Reductions in average and peak loads from 1993-1996/97, using the conservative methods described previously, were calculated to be approximately 70% and 90% respectively.

Attributing the observed reductions in load to particular remedial measures was more difficult and was performed somewhat simplistically. Due to the complex nature of the site and the variety of measures implemented concurrently, some assumptions were necessary to apportion load reductions to a certain mechanism. In doing so, assumptions and numbers were kept simple to reflect the degree of uncertainty involved. Load reductions for remedial actions are shown in Table 1.

Data indicated that approximately 90% of the generated load reduction was due to reductions observed at groundwater discharge points, specifically the Reynolds Adit. These reductions were attributed to the actions of backfilling/capping the mine pits and plugging of the adits. Therefore, it was assumed that 0.9(489 lbs/day) = 440 lbs/day of reduction was due only to these two concurrent actions. Monitoring well data indicated an approximately 50%+ reduction in peak groundwater level rise after capping, shown in Table 2. This figure is reasonable given observations of groundwater discharge flow rates over the same period. These values were interpreted as supporting a 50% reduction in infiltration to the mine groundwater pool, which was attributed solely to backfilling and capping of the mine pits. Because flow is directly proportional to loading, this reduction in filtration due to backfilling/capping translates to a similar reduction in loading 0.5(440 lbs/day) = 220 lbs/day. The remaining 50% of the groundwater load reduction (220 lbs/day) was attributed to an approximately 50% reduction in copper concentrations observed emanating from the Reynolds Adit after plugging, shown in Figure 4. It was assumed this concentration change was due only to adit plugging. This is a plausible scenario, as flooding the mine workings may prevent formation and subsequent rapid dissolution of secondary metal salts which can supersaturate contacting water (Plumlee, et al, 1995). The remaining 10% of total reduction was attributed to reductions in concentrations emanating from the French Drain Sump/HLP (shown in Figure 5), which was affected by many actions including HLP draining and Cropsy Waste Pile removal. This section of the site is located over a groundwater "divide" from the remainder of the site (MK, 1997) and was considered unaffected by adit plugging and pit backfill/capping.

Future land reclamation was also considered. Though evidence is often anecdotal, several authors suggest that reclamation can affect a substantial decrease in flow and acidity at surface disturbed sites. Gibson and Pantelis (1988) found that simple clay capping and revegetation of mine waste heaps at a surface mine site reduced infiltration through the heaps and into the underlying groundwater by 90%. Copper loads in the river draining the same site decreased approximately 75% in the first two years after completion of the project, despite the slow reponse of groundwater quality beneath the heaps to remediation. Further reductions were anticipated in 5-20 years as groundwater beneath the heaps begins to respond to



Estimated Initial Load Generated = 0.75 x (1993 Load) = 710 lbs/day
Estimated Current (Remaining) Load Generated = (1996 Load + 1997 Load) / 2 = 221 lbs/day
Total Load Reduction 1993-1996/97 = 710 lbs/day - 221 lbs/day = 489 lbs/day

Notes
1. Actual reporting loads were loads as measured at the sample point.
2. Water treatment loads were loads "removed" prior to reporting to the sample point.
3. The sum of the reporting plus water treatment loads indicates the total load generated.

Figure 2. Average Copper Loads Generated by Site as Measured at the Downstream Point of Compliance (WF-5.5).

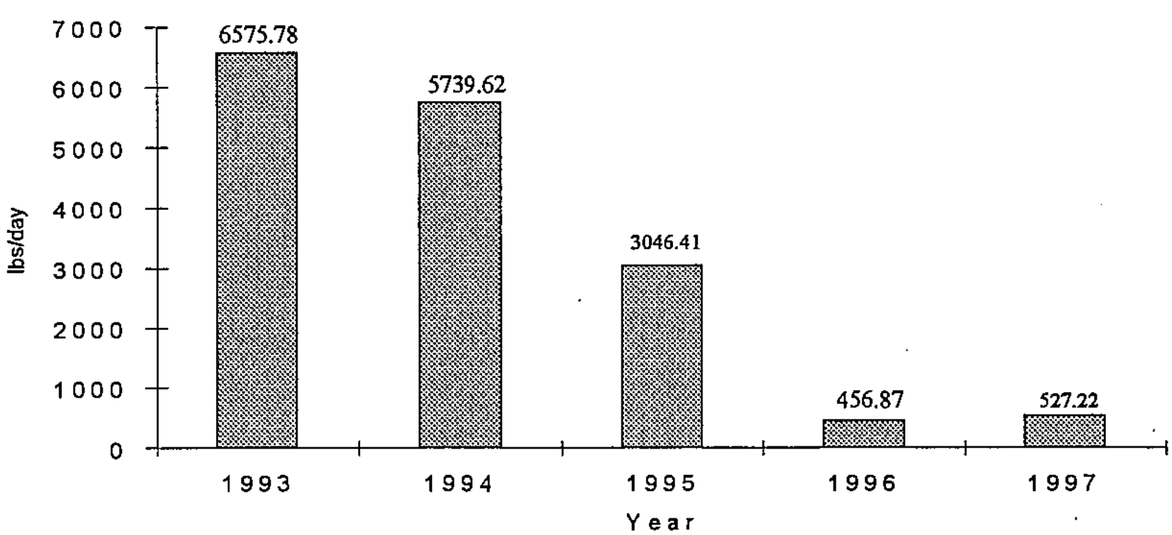


Figure 3. Sum of Four Largest Peak Point Source Loads by Year

Action	Mechanism	Calculation	Load Reduction
Pit Capping/Backfilling	Reduced infiltration to mine groundwater pool by est. 50%	(0.9)(0.5)(489)	220 lbs/day
Adit Plugging	Reduced average copper concentrations emanating from adits; remaining 50% of reductions in groundwater loads	(0.9)(0.5)(489)	220.lbs/day
Cropsy Waste Pile removal, HLP drawdown, etc.	Reduced water/rock contact times in the HLP/French Drain vicinity; remaining 10% of total load reductions	(0.1)(489)	49 lbs day
Reclamation, HLP capping, north pit capping	Projected reduction in infiltration to mine groundwater pool by further 50% for groundwater loads; projected increase in soil pH for surface loads	Groundwater (0.75)(0.5)(221) Surface (0.25)(221) Total	83 lbs/day 55 lbs/day 138 lbs day

Initial 1993 copper loads..710 lbs/day
Current (remaining) 1996/97 copper loads..221 lbs/day
Reduction in loads 1993-1996/97..489 lbs/day
Fraction of reduction 1993-1996/97 due to groundwater sources..............................90%
Fraction of remaining loads attributed to groundwater sources................................75%

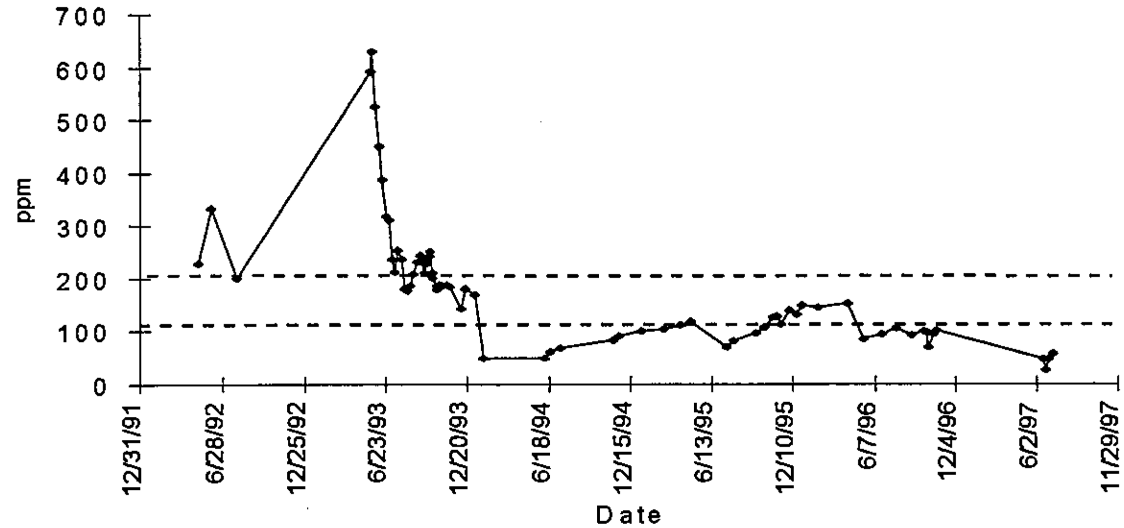
Projected loads after effects of land reclamation..83 lbs/day
Average load reduction due to water treatment 1993-1996 (temporary)........180 lbs/day

Table 1. Load Reductions for Remedial Actions.

Well Name	1994 Peak Water Level Rise (ft)	1995 Peak Water Level Rise (ft)	1996 Peak Water Level Rise (ft)	1997 Peak Water Level Rise (ft)	Average Percent Reduction 1994-1996/97
BORMW-2	209	167	57	95	64%
ABCMW-2	220	193	57	NA	74%
ABCMW-3	138	144	86	131	22%
Average %					53%

Notes:
1. Adit plugging was completed in late 1994; south pit backfill/capping and north pit backfill considered completed in late 1995.
2. 1994 was a normal snowfall year, 1995 and 1997 were high snowfall years, 1996 was low snowfall year.
3. Sampling at ABCMW-2 was not performed in 1997; average percent reduction for this well is probably lower than 74%.
4. Sampling in 1997 was not began until late May, therefore peak rise may be slightly higher as lowest water levels were not captured.
5. BORMW-2 and ABCMW-2 were strongly connected to groundwater beneath the pits; ABCMW-3 was only moderately connected. Including two strongly connected wells (compared to one moderately connected well) weighted the stronger connection heavier.

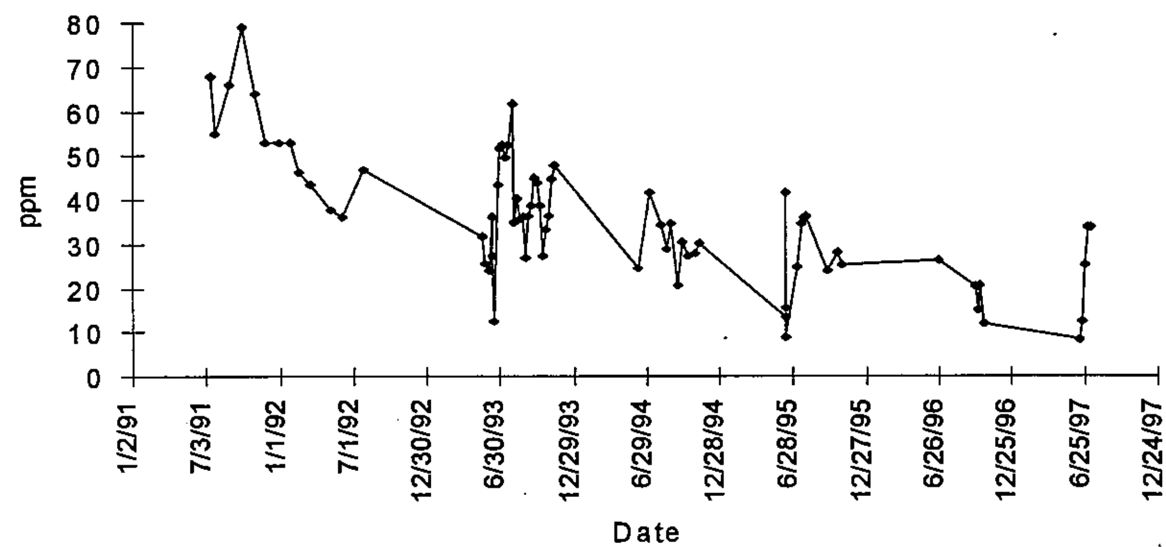
Table 2. Monitoring Well Data (From MK Corporation, 1997).



Notes

1. 1993 was an exceptional year; 1997 may have experienced dilution due to heavy flows.
2. Based on (1), average initial concentration estimated as approximately 200 ppm.
3. Based on (1), average current concentrations estimated as approximately 100 ppm.
4. Estimated net decrease in copper concentration approximately 50%.
5. Adit was plugged in late 1993.

Figure 4. Copper Concentration at the Reynolds Adit.



Notes

1. Readings were taken at sample point LPD-2, which measures a seep at the base of Dike1. Dike 1 encloses the HLP near the French Drain. The French Drain has been inaccessible since late 1995.

Figure 5. Copper Concentration near the French Drain.

remedial actions. Faulkner and Skousen (1995) found that backfilling and capping of surface mines, followed by revegetation, reduced total flow on twelve of sixteen sites studied, with an average of slightly over 50%. The same study indicated a 100% reduction in total acidity load on ten of sixteen sites in just six years, though all sites showed significant reductions. A study by Rastogi (1996) utilizing a reclaimed surface mine site as a control, showed that over a ten year span conventional reclamation alone reduced acidity in discharged water by 87%.

The mechanism for these reductions is believed to be three fold. First, capping prevents infiltration beyond the upper vadose zone in the area of the cap and excludes water from the most heavily acid generating materials. Second, topsoil improvements and revegetation increase the water holding capacity of the upper horizons (including vegetation) and greatly increase evapotranspiration. Last, permanent pH adjustment of soils halts surface acid generation. The results are a net decrease in total flow, an increase in the surface runoff to groundwater discharge flow ratio, and greatly improved surface runoff quality. Groundwater metal concentrations may also improve as metals held in microscopic pores both in the saturated and vadose zones are flushed over time.

In the Summitville case, a further 50% reduction in infiltration into the mine groundwater pool (due solely to future site wide reclamation and capping of the north pit and HLP) was assumed. This results in a further 50% reduction in groundwater discharge, thus providing a 50% reduction in current groundwater loads. Assuming groundwater loading is currently 75% of the total load produced (25% surface runoff), this amounts to (221 lbs/day)(0.5)(0.75) = 83 lbs/day. Also assuming that reclamation and past source removals will reduce current surface loads by 100% (again, due to increased soil pH from liming and exclusion of water from the extracted waste piles), the total reduction due to reclamation is then 81 lbs/day + 0.25(221 lbs/day) = 138 lbs/day. These assumptions lead to a value of 83 lbs/day of copper being generated by the site after the effects of reclamation and source removal are realized. The time frame for these improvements is unclear but at least ten years (to allow for establishment of vegetation and pore water response) will likely be required. Assuming a tentative target of 80 lbs/day (based on a 15 ton/year requirement negotiated by the State of Colorado and the mine operators in 1992), water treatment may no longer be needed.

Water treatment was handled separately. Though water treatment does not affect loads generated by the site (i.e. is not source attenuation), it greatly affects loads transmitted downstream and has played a critical role in interim control. Therefore, a theoretical reduction in load due to treatment was calculated for comparison. This value (180 lbs/day) was obtained by averaging the lbs/day of copper treated from 1993-96. This value is slightly lower than the current loading generated by the site, which is plausible, since nearly all of the generated copper loads in 1996 were removed by treatment. It must be stressed that this reduction is only temporary.

The effects of water treatment are very evident in a time graph of flow and copper concentration at WF-5.5, shown in Figure 6. This graph illustrates the consistent trend of decrease in concentrations, as well as fluctuation, observed post-treatment from 1992-97. It is important to note that in the past, concentrations peaked at the same time as did flow, which has the effect of maximizing loads. More recently, the trend has been the reverse, with the effects of dilution becoming pronounced. This trend minimizes loading and fluctuations. Though this graph reflects improvements across the site, it is certain that capture and treatment played a very large part in reducing both the magnitude of concentrations and the magnitude of fluctuations from year to year.

Overall, remedial measures have improved water quality, though extensive work still remains. Remedial measures employed to date have affected significant copper loading decreases but have been unable to completely alleviate the problem. Each remedial measure appears to have signficantly reduced acid rock drainage, but no single remedy could have addressed the variety of problems posed by the site. It appears that final reclamation may lead to attainment of water quality objectives without the need for water treatment.

Discussion

It is certain that extensive improvement has been achieved at Summitville. The large reduction in copper load observed at the compliance point is supported by observations of point sources around the site and water quality downstream. Though the effect of the individual remedial actions is not entirely certain, there is little doubt that when taken as a whole, remediation has been successful.

Though the apportioning of load reductions to individual remedial actions was performed somewhat simplistically, the assumptions employed to achieve that simplicity were both plausible and supportable. In light of the complexity of the site, this approach is the only one currently possible. The analysis showed that

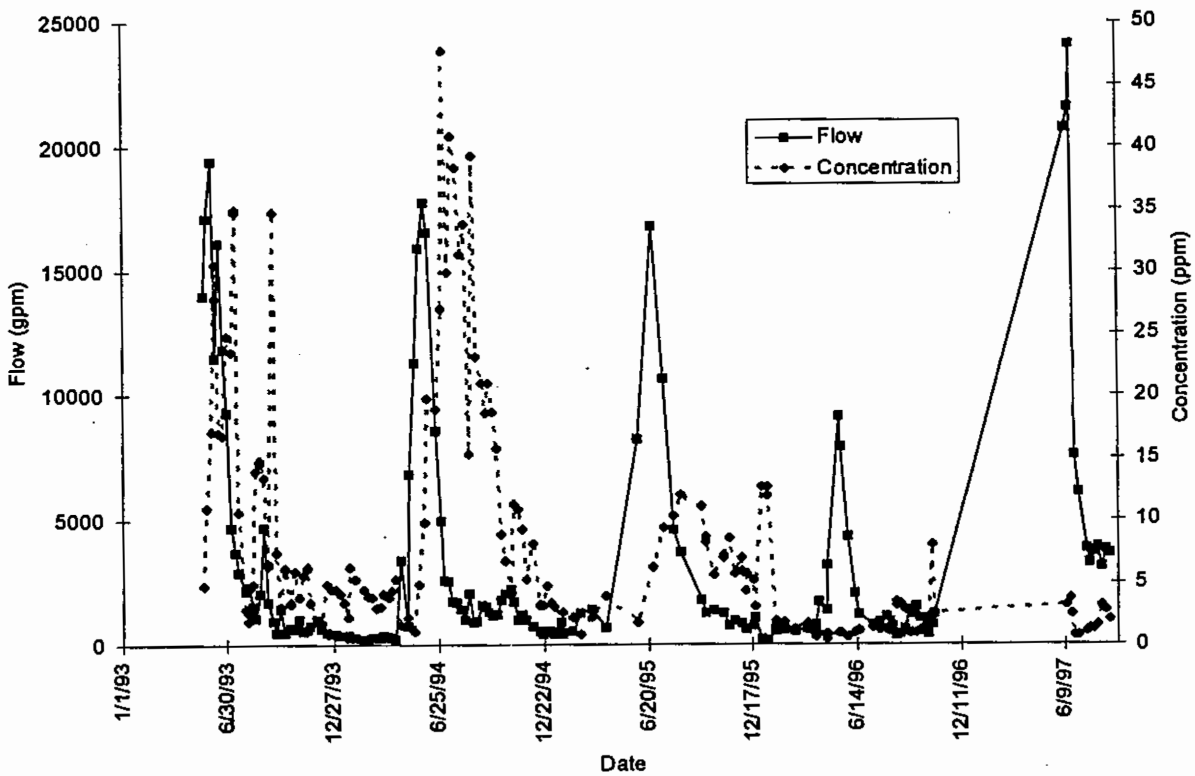


Figure 6. Flow and Copper Concentration at the Point of Compliance (WF-5.5).

each individual remedial action addressed a unique facet of the disturbance, and thus contributed a fraction of the total reductions in copper load observed. These fractions may not have been obtainable through other means. Though it is uncertain whether long term goalsare achievable, it is certain that all of the actions planned and employed, and perhaps others, will be necessary to make a reasonable attempt at achievement of these goals.

The prediction for the effects of remaining remediation, including revegetation, are speculative. The analysis was based on several key assumptions, which though supportable, are not clear cut. Therefore, considerable caution must be taken when addressing these predictions. Future decisions for remediation will be continue to be based on the observational approach, which allows for fluctuations from expected conditions.

Continued monitoring and analysis of remedial actions is ongoing. Though many of the remedial actions have effects that are well understood (such as pit backfill and capping), others are less clear. Adit plugging is still a relatively new remediation technology and its effects are widely debated. In the case of Summitville, it is still uncertain as to what effects adit plugging will ultimately have on groundwater quality, discharge rates, and potentiometric surfaces. It is safe to say, however, that it was a justified action in the short term. Discharge rates, copper concentrations, and loading have declined significantly since plugging occurred, though again, what fraction of the improvements are attributable to plugging is debateable.

It is difficult to classify the actions in terms of cost effectiveness, as many benefits are not discussed in this paper (such as HLP detoxification, water storage, erosion control, etc.). Also, some actions have had multiple effects (removal of a waste pile removes acid generating rock from saturated areas and provides backfill for filling in pits to reduce infiltration) and have been implemented simultaneously. However, some generalities concerning the cost effectiveness with regards to acid rock drainage control can be made.

Conventional water treatment, though necessary as an interim acid rock drainage control while source attenuation is being implemented, has proven very costly with regards to load reduction. To date, nearly 55% of the total project costs have been directly related to water treatment with no associated long term benefits. With the implementation of source attenuation, dependence on long-term water treatment will be reduced. Adit plugging has been the single most cost effective remedy, accounting for a significant fraction of load reduction at less than 1% of the total project cost. However, its long term effects and maintainability are still unclear. More proven technologies, such as source removal, pit backfilling, and capping, account for a large percentage of the project cost but also account for a very large fraction of the long term source attenuation.

Conclusions

The following conclusions can be drawn from this case study:

- Remediation at Summitville has been effective at reducing metal loads, though water quality standards have not yet been attained.

- Reclamation is predicted to further reduce metal loading such that little or no long term water treatment may be necessary to achieve water quality standards.

- No single remedial action is sufficient to alleviate the acid rock drainage problem at a complex site such as Summitville. Rather, a combination of actions, some less efficient than others, are necessary to meet water quality standards.

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