THE USE OF MULTIPLE AND SYNERGISTIC RECLAMATION TECHNOLOGIES TO IMPROVE WATER QUALITY FROM KYANITE MINE TAILINGS[1]

Gwendelyn Geidel and Frank T. Caruccio[2]

Abstract. Various reclamation strategies are implemented within a drainage basin containing three kyanite mine tailings ponds and the sequential strategies are based on each pond's unique geochemical and hydrologic characteristics. The Graves Mountain mine site in Lincolnton, Georgia, extracted kyanite from a quartzite-kyanite-pyrite host rock with associated sericite schist and iron oxides. During various stages of mining, tailings ponds were constructed on the south, west, and north slopes of the mountain and the acidic drainage from each set of tailings ponds effects a different drainage basin. Reclamation of the southern ponds was previously presented (Geidel et al., 1999), however, different reclamation strategies are implemented on each of the north ponds reflecting the unique hydrologic and geochemical characteristics of each set of ponds. The northern side includes three small tailings ponds and one settling basin from which the combined flows are discharged. The discharge from individual tailings ponds as well as the final discharge have been monitored for approximately eight years. The water quality from the final discharge prior to this study had a pH of about 2.5, acidity of approximately 800 mg/l as $CaCO_3$, high specific conductance, sulfate and metals. Due to variations in construction and discharge quality of the three tailings ponds, a number of reclamation technologies are employed within the drainage basin. These technologies include: an alkaline recharge trench (A-6); a 0.17 m surface layer of limestone on the unmined forest floor; a constructed wetland on the surface of one tailings pond (A-3); the addition of lime into the groundwater (A-4); the incorporation of two anoxic limestone systems (one vent and one drain) within the settling basin (A-2); and the construction of a wetland below the settling basin. The study showed that the various reclamation technologies significantly improved the overall water quality. Although each of the strategies independently produced ameliorative effects, the overall significant improvement was related to the synergistic effects of the combined technologies. As a result of the use of multiple reclamation technologies, the terminal water quality under low flow conditions (resulting from a three year drought) has a pH between 6 and 7, a low to negative acidity and significantly decreased metals concentrations.

Additional Key Words: acid mine drainage, acid rock drainage, alkaline recharge trench, limestone applications, constructed wetlands.

[1] Paper was presented at the 2002 National Meeting of the American Society of Mining and Reclamation, Lexington, KY, June 9-13, 2002. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

[2] Gwendelyn Geidel is a Research Professor of Geological Sciences and the Associate Dean of the School of the Environment, University of South Carolina, Columbia, SC
Frank T. Caruccio is a Distinguished Professor Emeritus of Geological Sciences, University of South Carolina, Columbia, SC.

Proceedings America Society of Mining and Reclamation, 2002 pp 41-57
DOI: 10.21000/JASMR020100041

https://doi.org/10.21000/JASMR02010041

Introduction

A pyritiferrous quartzite-kyanite ore body at the Graves Mountain site in Lincoln County, Georgia, was most recently mined from the early 1960's through the mid-1980's for kyanite and, at times, pyrite (Cook, 1985; Hartley, 1976). The processing entailed blasting, crushing and further wet-crushing the ore to a minus 28 mesh size. The minerals were separated from the slurry by flotation and the waste minerals, including quartz, micas, pyrophyllite, lazulite, rutile, ilmenite, geothite, hematite and often pyrite, were pumped to several tailings ponds. During various mining episodes, tailings ponds were constructed on the south, west, and north slopes of the mountain and the drainage from each set of tailings ponds effects a different drainage basin. The tailings ponds on the north side of the mountain are the oldest while those on the south side are the most recent and largest. Reclamation of these larger ponds was reported in Geidel et al, 1999.

The north side of the mountain contains a series of three tailings ponds and one sediment or storm water pond. While no mine records exist documenting the age of each pond, the upstream ponds were, most probably, constructed first and the lower ponds were subsequently constructed. Tailings were transported from the processing unit to the ponds through a series of pipes. Due to variations in the host rock chemistry and variations in the removal of minerals during the processing (most notably pyrite, FeS_2), the geochemistry and hydrology of each of the tailings ponds varies.

The north side drainage basin is further divided into several "Areas" based on either the physical characteristics or treatment of particular portions of the basin. Area 1 is the lowermost portion of the basin and contains the final constructed wetlands. The outflow from Area 1 currently meets NPDES permit pH requirements. The outflow (which has been minimal or non-existent most of the past two years due to the low precipitation) is pumped to the main treatment facility due to occasional elevated iron concentrations.

Area 2 is immediately upstream from Area 1 and is separated from Area 1 by an earthen dam; installed presumably when the area was actively receiving tailings from the ore processing. Area 2 contains some tailings, but may have been primarily used as a sediment and stormwater basin. Incorporated within the dam is a large diameter (0.6m (24")) pipe. During the modification of the sediment basin to a wetland and the incorporation of an anoxic limestone system (ALS), the pipe was converted to a standpipe with the addition of a 90^{o} elbow and 1.3 m (4 ft) of vertical pipe. The discharge from the standpipe is monitored and flows into Area 1.

Area 2 is also immediately below the dams of Area 3 and Area 4. Area 3 has a direct discharge to Area 2 while Area 4 has a overflow discharge pipe directed toward Area 3. Area 4 has been noted to discharge to Area 3 on only a few occasions, however, the Area 4 pond continually held water until recently. Even prior to the current 3-year low precipitation, there was little run-off from Area 4 except during major storm events. It was presumed, however, that there was a direct hydrologic connection between the two areas and that seepage from Area 4 flowed directly, via groundwater, to Area 2, based on seeps appearing at the base of the dam separating Areas 2 and 4.

Area 3 contains tailings and was converted into a wetland. After reclamation, the discharge, when flowing, has a pH around 6 and minimal iron concentrations. Above Area 3 is a forested valley which also contains tailings within the stream bed and within the flood plain on the valley floor. Within this upper area, three to six inches of limestone was spread on designated areas of the unaffected forested ground surface to increase the alkalinity of the ground and surface water (Caruccio and Geidel, 1996). Moving farther upgradiant, to the topographic drainage divide, the remainder of the basin was cleared, recontoured and revegetated during the post mining, reclamation stage. The mine office and associated equipment were located in this general vicinity, but were removed (and/or portions buried) when the operation ceased.

This description accounts for approximately one-half of the northern drainage basin. The other half (47.5%) is located east of Areas 1, 2, and 3 and covers approximately 15 acres. This portion of the drainage basin includes two tailings ponds (Area 4 and Area 6), undisturbed areas and reclaimed land. Area 6 is the uppermost tailings pond and Area 4 is immediately below. The surface discharge from Area 6 as well as, runoff from the un-mined portion of the property is channeled to Area 4. Area 4 is also hydraulically connected to Area 6 by seepage through the dam separating the two areas.

Remediation Technologies

Headwaters Reclamation and Alkaline Additions

The discussion of reclamation technologies will begin from the head of the drainage basin and move down stream to the final discharge from Area 1 and is shown in Figure 1. Within the headwaters, the vegetation was cleared and the crushing and flotation processing occurred. It is presumed that the area was not mined as the pits are clearly defined and remain intact, however, the area was cleared and recontoured to provide a suitable site for the office and processing units. At the completion of the operation in the mid 1980's, the office and processing units were removed and the surface regraded and reclaimed. Subsequent reclamation efforts in 1997 included additional lime (10 t/ac), fertilizer and seed. A well was drilled at the drainage divide to determine the water quality from this area. In the lower section, a 8cm (3") thick layer of limestone was placed on the surface as part of the alkaline additions for ground water and run-off remediation discussed below.

During the early phase of the active operation, tailings were conveyed from the processing unit to one of three tailings ponds in the northern drainage basin. These are currently designated as Areas 3, 4 and 6. Area 3 is in a separate sub-drainage basin on the west side and Areas 4 and 6 are in an eastern sub-basin. Although the conveyance pipes were removed long ago, the routes can be located due to channeling occurring in the vicinity of the pipes and the excess tailings on the surface which were presumably spilled from the pipes. The tailings are comprised of fine-grained quartz, clay and minor amounts of pyrite (on the order of about 2%). Between the processing units and the tailings ponds, forested areas are present.

Alkaline Additions for Groundwater Remediation

Above Area 3, a significant number of tailings were located in the intermittently flowing stream channel approximately 215 m in length. The water quality from the stream, sampled immediately upstream from where it entered Area 3 tailings pond, was initially acidic and was the subject of alkaline additions reported in Caruccio and Geidel, 1996. In summary, the forest floor was covered with 8cm (3") of coarse grained limestone in the summer of 1995 and impacted the ground water and runoff with alkalinity calculated to offset the amount of acid

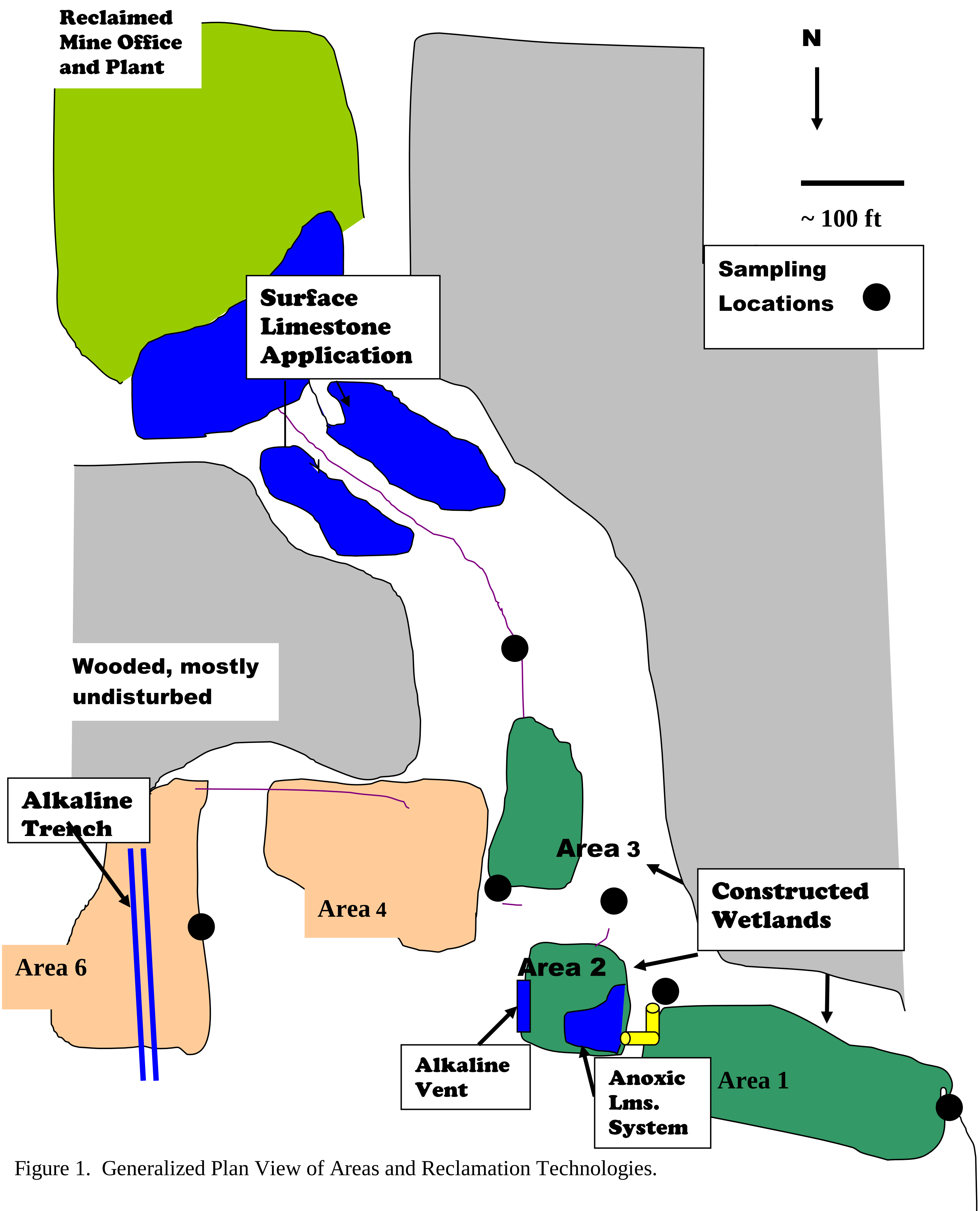

Figure 1. Generalized Plan View of Areas and Reclamation Technologies.

produced by the tailings in this area. The long-term results have shown a decrease in the total acid load, but pH values remain relatively stable at between 4.2 and 4.5. The discharge from this treatment flows into Area 3.

Area 3 Constructed Wetland

Area 3 is a tailings pond constructed in a steeply incised valley and the containing dam of which was built by pushing rock and clay from the existing valley floor to create a dam at the terminal end of the pond. It is estimated that the tailings are up to 5m (15 ft) deep in the terminal end and 1-2 m thick at the inlet end. On the surface of this tailings pond, an anaerobic wetland was constructed. Although numerous wetlands have been constructed (Hedin, R.S., and R.W. Nairn, 1992; Skousen, et al., 1998), few have been constructed on the surface of a tailings pond. To maximize flow through the tailings, two sandbag diversion dams were constructed with spillways on opposite sides of the pond to provide flow through the maximum length of wetland. The wetland was constructed with approximately 15-20 cm (6" to 8") of coarse (2.5-5 cm (1-2")) limestone placed on the surface of the tailings, covered with 30-45 cm (12" to 18") of mushroom compost, then planted with cattails. One 5cm (2") PVC peizometer was installed on the upstream side of each of the two diversion dams. The construction was completed during the summer of 1994. The water quality discharging from the wetland has been monitored through time.

Area 3 discharges to Area 2 via a 10-cm (6") pipe installed within the sandbag dam at the lowest end of the pond. Area 2, however, is the confluence of the flow from the western sub-basin (Area 3 and above) and the eastern sub-basin (Areas 4 and 6). Therefore, using the approach of discussing the upper drainage basins first, the Area 6 study will follow.

Area 6 Alkaline Recharge Trench

Area 6 is the uppermost tailings pond in the eastern sub-basin. An assessment of the Area 6 tailing pond, which is currently vegetated with pine, indicates that the tailings pond contributes significantly to the acid load entering the adjacent and lower pond (Area 4). Tests showed that the acidity could be neutralized and positively affected by imported alkaline producing material. Field studies of infiltration rates indicated that the Area 6 tailing pond was porous and had high infiltration rates, on the order of 25-30 cm (10 to 12") per hour. A detailed hydrologic study with 11 peizometers indicate that acidic water is discharged via groundwater from Area 6 to Area 4 and demonstrated that the Area 6 tailings pond is hydraulically connected to Area 4. These data supported the use of an alkaline trench (Caruccio et al, 1985) to abate the acid levels transferred from Area 6 to Area 4.

A trench, 2m (6') wide, 68m (204') long and 1.2m (3.5') average depth, was constructed parallel to the dam and approximately 3.5 to 5m (10' to 15') set back from the center of the dam. The material excavated from the trench was placed between the trench and the dam. Should a storm event occur that leads to overland flow of the precipitation, this configuration allows for diversion of the surface flow into the trench; consistent with the objective of the trench to provide for maximum infiltration from an alkaline source.

Following construction of the trench, a layer of soda ash (Na_2CO_3) briquettes was applied at a rate of 1 pound /ft^2 and placed in the base of the trench. Next, a 1m (3') layer of coarse-grained limestone (0.5-2cm (1/4 to ¾ inch)) was placed over the briquettes. Due to the high infiltration rates of the tailings material, most rainfall does not run-off, but infiltrates where it strikes the tailings. Therefore, in order to provide for a water source to convey the alkalinity into the tailings, a drip irrigation system, commonly used in land irrigation, provided recharge to the tailings pond.

The purpose of this treatment was to provide an alkaline wetting front which in turn, neutralizes the existing acidity and displaces the iron oxidizing bacteria (*thiobacillus ferroxidans*) which accelerate the oxidation of pyrite. Neutralizing the acidity in the uppermost tailings pond and rendering the ground water alkaline will have a positive impact on the remainder of the sequence of tailings ponds and constructed wetlands.

Area 4 Direct Lime Addition to Groundwater and Subsequent Tailings Removal

Area 4 is the largest of the three tailings ponds and receives water from four sources: regional groundwater, surface water, seepage from the dam between Area 6 and Area 4; and direct precipitation. The water quality in Area 4 is impacted by these sources, as well as by the tailings contained within the Area 4 tailing pond. The interrelationship between these sources is important in determining not only the impact on the water contained within Area 4, but in determining the most effective treatment methodology. In the summer of 2000, three large holes (3.5m x 5m x 5-7m)(10'x15'x 15-20' deep)) were excavated, as well as a trench approximately 1.5 m (5') deep x 4m (10') wide and 17m (50') long. Screened well pipes were installed in each hole and 100 lbs. of lime added to each of the three holes. Water quality of these holes was monitored. During Spring 2002, the treatment of Area 4 continues and includes the removal of the tailings. Depending on the water quality, wetlands may be constructed in addition to an alkaline drainway and small-scale alkaline vents.

<u>Area 2 Constructed Wetland and Anoxic Limestone Drain and Vent</u>

As noted above, the discharges from the three tailings ponds flow into Area 2 settling pond or basin. The dam containing Area 2 basin had a large diameter pipe installed in the dam and through which water was discharged. To take advantage of the existing bottom drainage, an anoxic limestone drain or system (Skousen, J.G. and B.B. Faulkner, 1992) was constructed within the basin in the vicinity of the drain. A layer (15 -18 cm (6-8")) of coarse-grained limestone was placed over the bottom of the entire basin for the wetland base. Around the drainpipe (approximately 500 ft^2), limestone 1-1.3 m (3 to 4 feet) thick was spread for the anoxic limestone system. A sheet of 20-mil plastic was placed over the thick layer and the plastic covered with soil. The remainder of the basin was converted to a wetland with a 15-cm (6") limestone layer covered with 45 cm (18") of mushroom compost and seeded with cattails. On the downstream end of the discharge pipe, a 90^o elbow was added to the pipe and a 1.3m (4-foot) riser pipe added to control the water level in the pond. The discharge from the pond is monitored through the riser pipe.

Two years later (in October, 1996) due to significant seepage into Area 2 through the Area 4 dam, a limestone vent was installed at the upper end of Area 2 to intercept the seeps. The vent measured 10 m (30 ft) by 3m (9 ft) by 1.3m (4 ft) deep. The excavation was filled with coarse (>2,5 cm (1") limestone. After completion, seepage was noted to flow upward through the vent and discharge into Area 2.

Area 1 Constructed Wetland

Area 2 discharged to an intermittently flowing stream (Area 1), the configuration of which was conducive to the construction of an anaerobic wetland. The stream segment designated for the wetland was approximately 66m (200') long and approximately 11 m (40') wide. The area was divided into six sections; each separated by a sandbag dam approximately 0.9 m (3') high. The spillway from each dam was located on alternating sides of the wetland to provide the maximum flow path through the wetland.

The wetland was constructed in the summer of 1994 in a manner similar to that of Area 3 and included: 15-18 cm (6 to 8") of coarse grained limestone in each section, then 60 cm (18") of mushroom compost, then the water was allowed to fill the wetland and it was subsequently planted with cattails. Above each sandbag dam, a 5 cm (2") PVC peizometer was installed into the limestone bed to provide a method to monitor selected segments of the wetland. At the terminal end of the wetland, the flow is discharged to a sump area that can be pumped to a treatment pond or discharged to a stream.

In May 1996, a short duration, high intensity rainfall event caused significant run-off. To prevent the breaching of the dam in Area 4, the Area 4 flow (which was very acidic) was diverted to the lower wetlands. The high flow rates in Area 1 created an erosion channel on the south side of the wetland and disturbed the wetland water quality, limiting the wetlands ability to function. As a result, the wetland was reworked in 1997 by placing additional limestone in the channel and placing hemp bags filled with peat moss and weighted with limestone on top of the layer of limestone. Cattails were replanted in the area.

Additionally, in the summers of 1998 and 1999 the entire northern drainage basin (approximately 30 acres) had 10 tons/acre of lime spread over the area by air application.

Results and Discussion

The water quality emanating from the western portion of the drainage basin (headwaters to Area 3) is measured by the final discharge from Area 3 and is shown in Figure 2. The data from this discharge indicate that during the second and third winters (which corresponded with periods of higher flow) the pH dropped and acidity levels increased. During the summer, however, and since 1997 when flow has been unusually low, the pH is high (about 7.5) with a corresponding lower acidity. During the drought, a number of storm events occurred, one of which was Tropical Storm Helene in September 2000, which provided 4.22 inches of rain. The pH of the Area 3 discharge during this event was 6.16. Since then, there has been no flow from

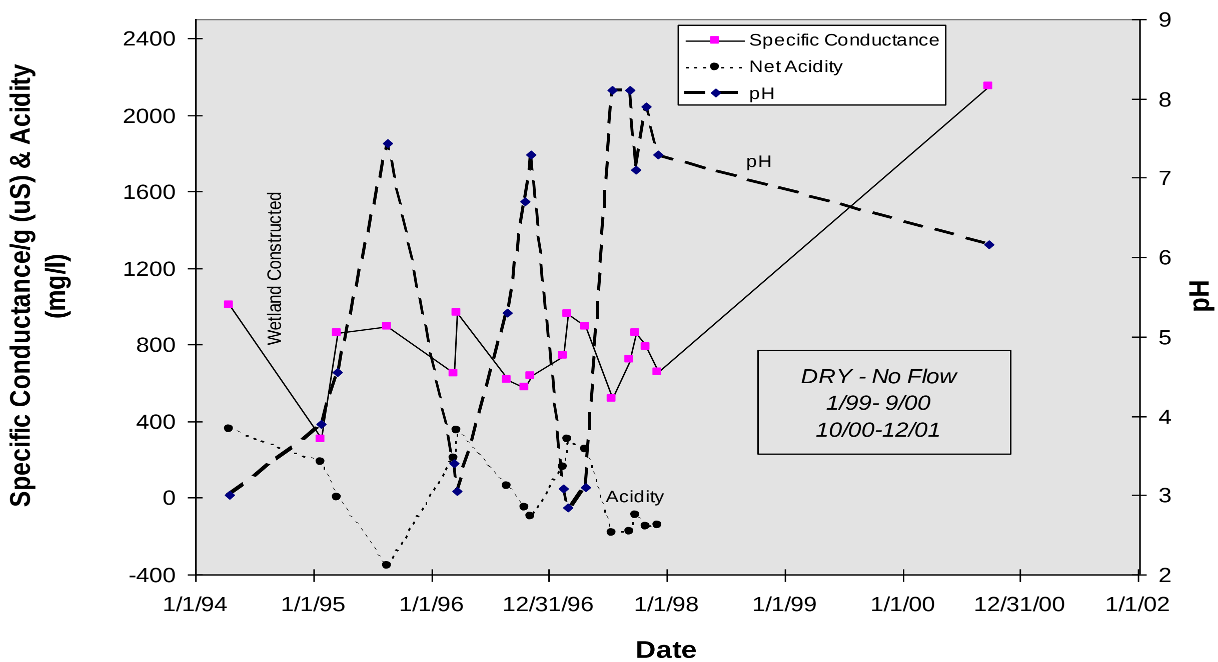

Figure 2. Area 3 Constructed Wetland Discharge.

that discharge point during sample collection times. Since December 1999, the entire wetland has been dry. The sedges remain although grass species and trees are encroaching throughout the area.

Upstream from Area 3, the discharge from the surface application of limestone has been dry since December 1999. Prior to that time, although the flow was intermittent, the flow was often in excess of 5 gpm. In September 1998, Tropical Storm Earl provided over 7.4 inches of rainfall over a two day period. The flow from this point was approximately 20 gpm with a pH of 5.2 and specific conductance of 83 µS. Specific conductance, as an indicator of the ionic strength of a sample and the inorganic constituents shows excellent correlation with sulfate ($r^2 > 0.9$). This compared to a rainfall quality of pH 3.55 and specific conductance of 12.5 µS.

Area 6 and Area 4 coalesce and are discharged into Area 2. During periods of high intensity rainfall, flow from Area 6, as well as run off from the upper portion of the basin, is discharged via a ditch to Area 4. As noted above, the discharge ditch was modified prior to the alkaline trench installation and the quality of the water discharging to Area 4 during Tropical Storm Earl included a pH of 7.02 and a specific conductance of 55 µS. However, the ground water discharging from Area 6, as monitored with the 11 piezometers at the base of the Area 6 dam, indicated acidic conditions as shown in Figure 3 which are water quality from three of the piezometers, Wells 6, 7 and 8. The increasing pH trends are attributed to the effect of the alkaline trench on ground water quality. As noted in Figure 4, the water level elevations have decreased with time and excavations in February 2002, indicted that the water level was nearly 5m (15') below the bottom of wells 1 and 7.

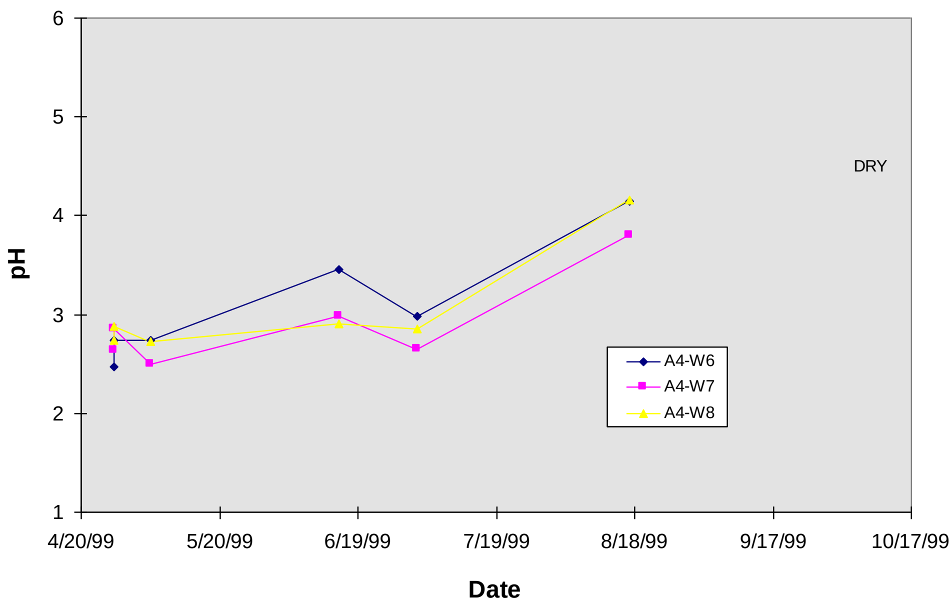

Figure 3. Groundwater samples from base of dam separating Areas 4 and 6.

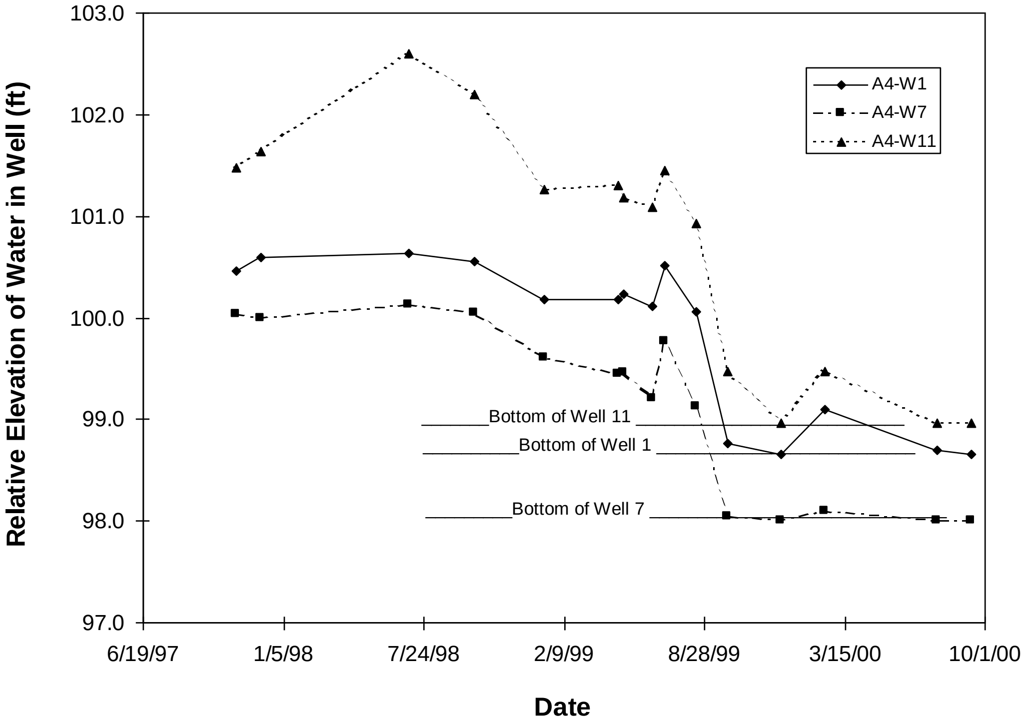

Figure 4. Area 4- Wells 1, 7 & 11: Water level elevations with time.

Area 4 surface water has been monitored and is shown in Figure 5. Approximately one year following completion of the alkaline trench, the water quality in Area 4 had improved. This may, in part, however, be due to dilution during storm events. From 1993 until early 1999, Area 4 had standing water with a pH of 2.5 –3.2 and acidity values from 3500 mg/l (in 1993) to 500 mg/l (in 1999) and it was assumed that the tailings pond was saturated. During excavations in 2000, is was determined that, although the tailings were up to 25 feet deep, a clay layer creating a perched water table, occurred at about 5 feet. Groundwater samples from the surface of the clay layer had a pH in the range of 3.2 to 3.5 and significantly lower specific conductance values (150 to 200 µS) compared to surface water values of 3000 uS to 300 uS. Water from Area 4 has, on occasion, discharged to Area 3, but it is presumed that similar to the dam separating

Areas 4 and 6, that water is seeping through the dam to Area 2 as indicated by the seeps at the base of the separating dam.

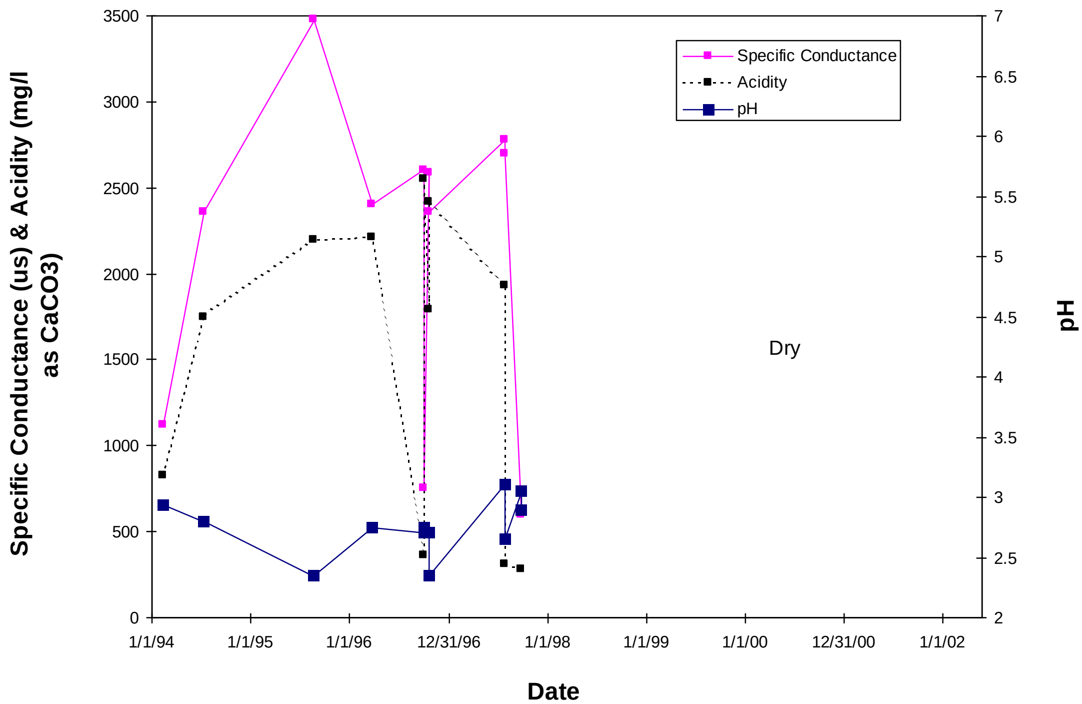

Figure 5. Area 4 Water Quality.

Area 2 is monitored through the standpipe, which is the outflow for the anoxic limestone system, as well as through an overflow pipe installed to prevent the breaching of the dam during periods of high flow. Needless to say, the overflow pipes have not been used, except for one or two rainfall events during the past several years. With the exception of the summer and fall of 2001, some flow has occurred through the standpipe and the results are presented in Figure 6. Through 1998, flow through the standpipe averaged between 3 and 4 gpm, however that decreased and, in the spring of 2002, discharge was about 0.5 gpm with a pH 6.4 and specific conductance of approximately 1400µS. The higher pH values suggest that the anoxic limestone system has been effective under low flow conditions.

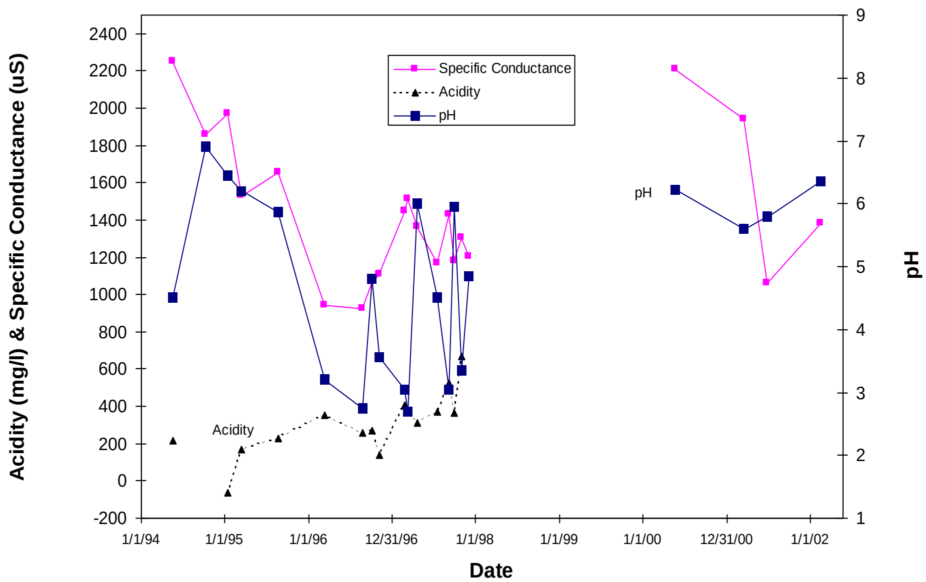

Figure 6. Area 2 Discharge through standpipe.

The standpipe of Area 2 (Fig. 6) is the influent water for Area 1, the final treatment segment in the drainage basin. Prior to the reclamation efforts described above, the pH from this discharge was approximately 2.8 with an acidity between 700 and 900 mg/l. As shown in Figure 7, the pH during the past two years has been maintained between 6 and 6.5 with an occasional fluctuation below pH 5. The specific conductance measurements are given in Figure 8 and, based on the increasing values, indicate that significant neutralization is occurring. In the field, this is substantiated by the amount of iron that is precipitating as the water seeps through the dam.

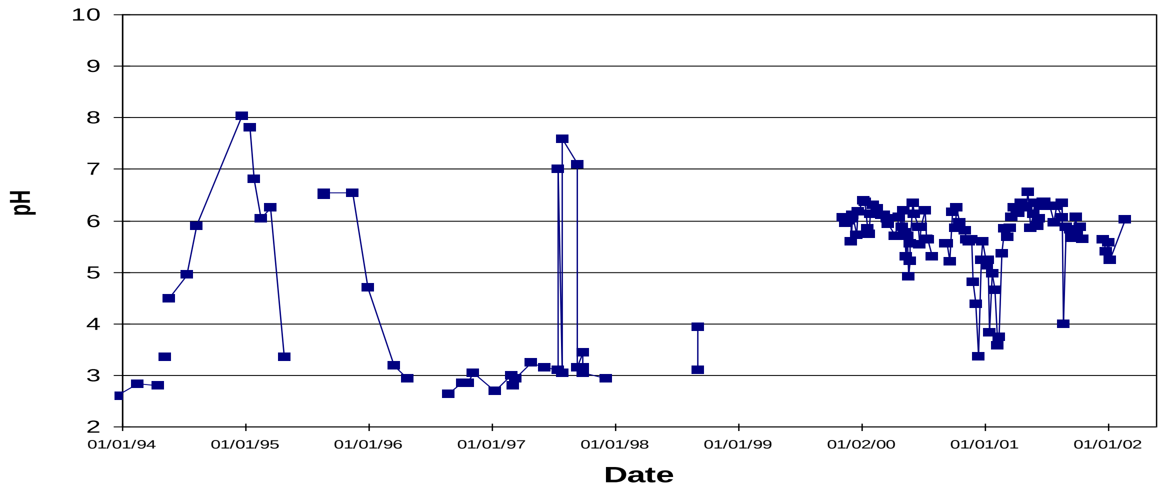

Figure 7. Final discharge pH.

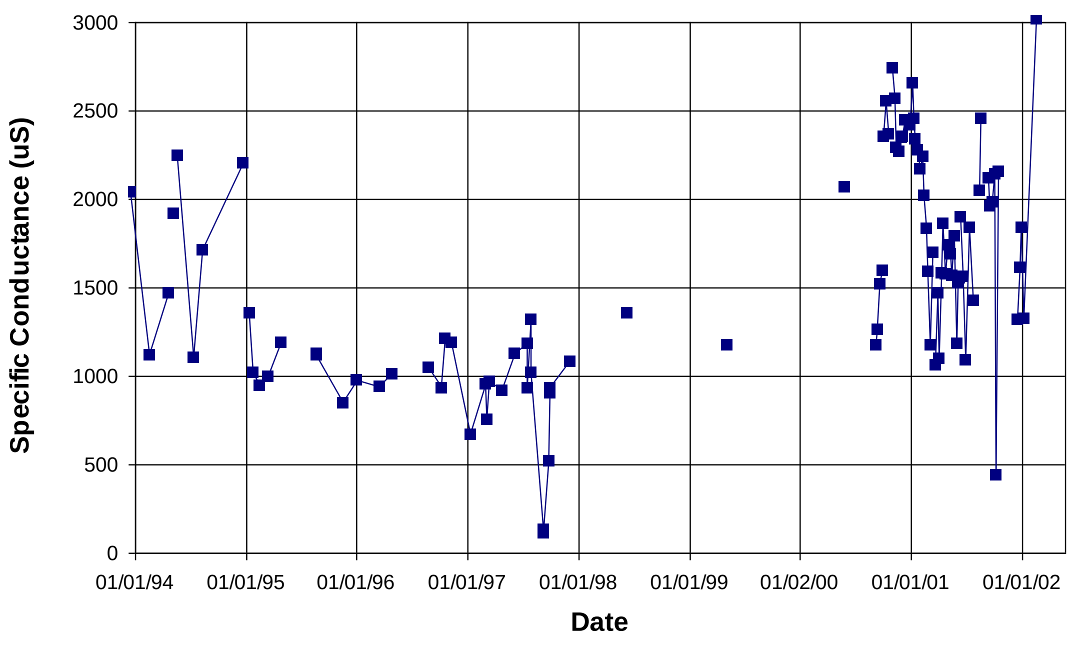

Figure 8. Final discharge specific conductance (mimics sulfate and acidity data).

Summary and Conclusions

The numerous treatments that have been applied in portions of the northern drainage basin at the Graves Mountain site in Lincoln County, GA, have sequentially lead to an overall improvement in water quality using passive systems. The initial water quality discharge (based on approximately six months of data) had a pH of approximately 2.5, acidity of 700 to 900 mg/l as $CaCO_3$, iron of about 360 mg/l and a specific conductance varying from 1100 to 2200 µS. these values have been significantly improved. The combined effects of alkaline additions, reclamation, constructed wetlands, alkaline trenches, and anoxic limestone systems, has improved the water quality at the discharge point to a pH between 5.5 and 6.5, lower acidity values (-200 mg/l net acidity (or 200 mg/l alkalinity) to about 100 mg/l acidity (Figs 7 and 8). Iron levels have decreased and significant iron loads have deposited in the wetland. In the vicinity of the Area 2 discharge, nearly 1.5 feet of iron and associated metals have precipitated at the base of the discharge pipe. In an effort to continue the treatment of the area so that the pH is consistently above pH 6.0, the final stage of the reclamation plan includes the removal of tailings from Area 4 and the installation of additional passive systems within the area from which the tailings are removed. The removal of the tailings and completion of the passive systems is scheduled for completion during the spring of 2002.

Acknowledgements

We wish to acknowledge and thank Combustion Engineering, Inc. for their support of this study.

Literature Cited

Caruccio, F. T., G. Geidel, and R. Williams. 1985. Induced alkaline recharge trenches – an innovative method to abate acid mine drainage. In: 6th WV Surface Mine Drainage Task Force Symposium. Morgantown, WV.

Caruccio, F. T. and G. Geidel, 1996. Limestone additions to affect changes in loading to remediate acid mine drainage. American Society for Surface Mining and Reclamation, Knoxville, TN. May 18-23, 1999. pp. 695-700.

Cook, R. B., Jr., 1985. The Mineralogy of Graves Mountain, Lincoln County, GA. The Mineralogical Record, Vol.16, no.6, pp. 443-458.

Geidel, G., F. T. Caruccio, and E. R. Dotson, 1999. Reclamation of kyanite mine tailings with surface reconfiguration. American Society for Surface Mining and Reclamation, Scottsdale, Arizona, August 13-19, 1999, pp.

Hartley, M.E.,III, 1976. Graves Mountain. Georgia Geological Society, Field Trip Guidebook, Vol 16, Pp. 42-52.

Hedin R.S. and R.W. Nairn, 1992. Designing and sizing passive mine drainage treatment systems. In: Proceedings, 13th West Va. Surface Mine Drainage Task Force Mtg., Morgantown, WV.

Skousen, J.G. and B.B. Faulkner, 1992. Preliminary results of anoxic limestone drains in West Virginia. In: Proceedings, 13th West Va. Surface Mine Drainage Task Force Mtg., Morgantown, WV.

Skousen, J., A. Rose, G. Geidel, J. Foreman, R. Evans, W. Hellier, and ADTI, 1998. A Handbook of Technologies for Avoidance and Remediation of Acid Mine Drainage, ADTI, WV NMLRC, Morgantown, WV. 131 p.