

COMPARISON OF HYDROLOGIC CHARACTERISTICS FROM TWO DIFFERENTLY RECLAIMED TAILINGS PONDS; GRAVES MOUNTAIN, LINCOLNTON, GA¹

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Abstract: This study compares and evaluates the hydrologic characteristics between two kyanite ore process tailings ponds that were reclaimed with different reclamation strategies; one reclaimed with an impermeable membrane and the other with an open, surface reconfiguration methodology. During the extraction and processing of kyanite ore from the Graves Mountain mine, Lincoln County, Georgia, fine grained tailings were produced. The tailings were transported by slurry pipeline to various tailings ponds which were created by the construction of dams using on-site materials. The first study site, referred to as the Pyrite Pond (PP), was constructed and filled during the 1960's and early 1970's. In early 1992, the PP was capped with an impermeable membrane, covered with a thin soil veneer and vegetated and in 1998 the upslope reclamation was completed. The second tailings pond, referred to as the East Tailings Pond (ETP), was constructed and filled in the 1970's and early 1980's and was reclaimed in 1995-96 by surface reconfiguration and the addition of soil amendments. Piezometers and wells were installed into the two tailings ponds and also in close proximity to the tailings ponds. While the initial study was aimed at comparing the two reclamation strategies, it became apparent that the ground water was a dominant factor. Results of the evaluation of the potentiometric surface data for varying depths within each tailings pond indicate that while both tailings ponds exhibit delayed response to precipitation events suggesting infiltration effects, the delay in the ETP deep wells and PP wells could not be adequately described by a surface infiltration model. Further consideration of the surrounding well data, coupled with the tailings cross sections and water levels, suggest that the hydrologic characteristics of both tailings ponds are significantly influenced by base flow infiltration and ground water seepage into the upgradient areas of the tailing ponds.

Additional Key Words: acid mine drainage, acid rock drainage, dry cover, impermeable cover, permeable cover.

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Introduction

During the extraction and processing of the kyanite-quartzite-pyrite ore from the Graves Mountain mine, Lincoln County, Georgia, the kyanite was extracted and fine grained waste tailings were produced. The waste minerals included quartz, muscovite, paragonite mica, pyrophyllite, hydrated kyanite, lazulite, rutile, ilmenite, goethite, hematite and, when not distributed as product, pyrite. (Cook, 1985; Hartley, 1976). The tailings were transported from the processing plant by slurry pipeline and gravity flow to various tailings ponds which were created by the construction of dams in areas incorporating existing incised drainage pathways. A number of the “ponds” were constructed by removing or scraping the surface soil, most of which was likely incorporated into the dams, and constructing dams to create holding ponds with depths ranging from 7m to 24m (20 to 80 ft) to accommodate the storage of slurry transported tailings. The subsequent physical and chemical weathering of the mineral assemblages within the tailings ponds and their inter-reaction with the aqueous systems produced acidic discharges with elevated metal and sulfate ions.

Given that the majority of the tailings are composed of silicate minerals, and primarily quartz, the weathering reactions are dominated by pyrite oxidation and clay hydrolysis, with pyrite oxidation accounting for the primary reactions significantly impacting water quality. The general chemical reactions defining the oxidation of pyrite and the production of acidity, sulfate and metals are well known and the resulting impacts on water quality have been documented in many scenarios including coal mining (Skousen, et al. 1998, Geidel and Caruccio, 2000), mineral mining (Lappako, 2002) and various anthropogenic activities (Daniels and Orndorff, 2003). As a result of the on-going reactions and changes in water availability, the tailings ponds represent geochemical and hydrologic systems that change and evolve with time.

The durable quartzitic ore-body host rock within the metamorphic sequence rises about 100 m (300 ft) above the surrounding landscape. Water discharges from this site, whether ground or surface water flow, originate primarily from the site and discharge radially into ephemeral, intermittent, and first order streams. Given the strike and dip of the deposit coupled with the method of mining and processing, the flow direction is predominately towards the west and then to the south and north. Discharges from several of the tailings ponds, subsequent to treatment, are discharged into the streams. While a number of tailings ponds exist on site, the

two primary ponds for which hydrologic data are available and which are evaluated in this study are the East Tailings Pond and the Pyrite Pond.

East Tailings Pond

Reclamation Summary

The East Tailings Pond (ETP) is approximately 31 ha (77 ac) in areal extent and tailings were placed into the pond to resultant tailings depths of about 15m to 23m (46 to 75 ft). The East Tailings pond dam structure was constructed primarily to the South and East, with natural boundaries occurring to the north and west. The downslope / outslope southern portion of the dam is approximately 21m (50 ft) tall and the eastern outslope is approximately 6 to 10 m (20 to 30 ft) tall. Upstream and northwest of the ETP is another tailings pond which was constructed prior to the ETP, called the West Tailings Pond (WTP). When the WTP became filled, the ETP was constructed and tailings were diverted to the ETP.

Kinetic leaching studies (Bradham and Caruccio, 1995) of collected samples from the ETP indicated that most of the acidity was contained in the interstitial water and that the tailings produced only minor amounts of acidity (on the order of less than 0.15 mg/g tailings/wk after 80 days). The sandy silt texture (75-80% fine to very fine sand, 8-13% silt and 10% clay) and the slurry pipe distribution of tailings during the ore processing, provided for variations in the moisture/water content of the tailings. The driest and most coarse material was in the northern portion of the pond while the most moist and often thixotropic conditions, coupled with a higher percentage of silt and clay sized particles, occurred in the southern portion of the pond. The average water content from three locations with samples collected at 0.3m (1ft) intervals to a depth of 1.7m (5ft) varied from 29.3% (Ww/Ws) from the 0.6-1.1m (2-3ft) depth to 39.9% from the 1.3-1.7m (4-5ft) increment. Overall, the average water content was 34.5% with a range of variation from 9.0% to 42.3%. (Geidel, et al., 1999).

During the spring of 1996, the ETP was reclaimed using small farm equipment (due to the thixotropic nature of the tailings). Straw, to prevent the wicking effect of acid from within as well as a source of organic matter, was spread at a rate of 1084 bales/ha (15 cm (6 in) thick) and lime was spread at a rates of 90 to 135 Mg/ha (40 to 60 tons/acre) based on test plot data as well as the analysis of 19 samples. This mixture was disked into the top 30cm (12 in) of tailings. Subsequently, ridge and furrows were constructed by plowing the ETP with a small tractor with

a modified plow implement which constructed the ridges and furrows of appropriate size. Due to the nature of the tailings, the tractor on occasion had to be removed from the tailings with a series of winches and vehicles. Once the surface topography had been modified with the ridges and furrows, the seed and fertilizer were applied by a modified crop dusting airplane. The straw and tackifier, which could be spread from a distance, was applied by surface application.

The revegetation has been successful and by 2012, approximately 2/3 of the tailings pond is covered with grass and shrub vegetation, including *Baccharis halimifolia*, and approximately 1/3 is forested with a variety of pines (*Pinaceae*), yellow poplar (*Liriodendron tulipifera*), sweet gum (*Liquidambar styraciflua*), willow (*Salix*) and oak (*Quercus*). In addition, the surface is developing a soil profile in the upper 1-2cm and has increased levels of organic carbon. Most importantly for this study, the surface soils are no longer thixotropic and the water table is not at the surface. During periods of high rainfall, some surface water is present and given sufficient intensity and duration, precipitation runoff occurs and collects in the southwest corner of the ETP. The pH of the runoff, post reclamation, continues to be maintained between pH 6 and 7 since 2002.

Hydrologic study

In an effort to evaluate the effect of the reclamation on the hydrology of the tailings pond, two shallow piezometers, approximately 1.2m below ground surface (bgs), were installed in 2003 in the general vicinity of the original vegetation test plots. One was installed approximately 30m from the dam (EP-A) and the other approximately 150m from the dam (EP-B). At the time of installation, the water level in EP-A was approximately 1.0 m bgs and in EP-B, approximately 0.5 m bgs. Within a year, EP-A was consistently dry and EP-B, during precipitation events, had water level elevations between 0.1 and 0.5 m bgs, but dry following no rain events, suggesting leakage.

In 2010, to evaluate the impact of the reclamation efforts on hydrology and water quality, two sets of wells with three wells per set were installed using direct push methods (Geoprobe[®]) mounted on a small remote controlled vehicle so as to minimize the impact on the ridge and furrow configurations. The first set (ETP-1: A, B, C) was installed in close proximity to EP-A. The second set (ETP-2: A, B, C) was installed to monitor the deepest tailings location. In each set of wells, well A was installed to the base of the tailing and the lowest 3m (10 ft) were

screened, B was installed approximately one-half the depth from the surface to the base of the tailings with the bottom 1.6m (5ft) screened and the third (C), was installed about one-half the depth between B and the surface with the bottom 1.6m (5ft) screened. The configuration of the well locations as well as a cross section of the tailings pond showing the maximum depth of the tailings are shown in Figs. 1 and 2.

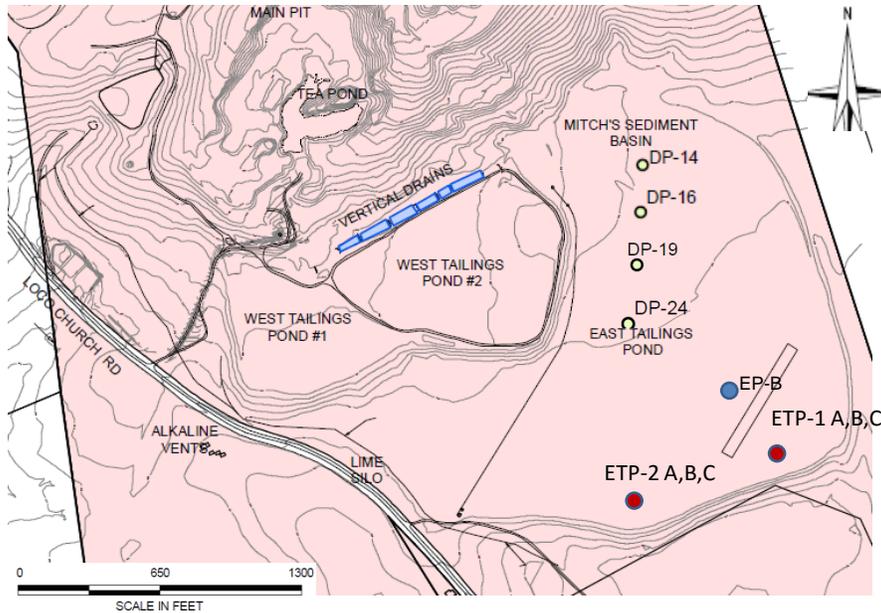


Figure 1. Location of ETP wells (red) and EP peizometers (blue) in East Tailings Pond. (DP locations, used to determine depth of tailings and water level only, were bored by direct push methods)

Well cluster ETP-1 was in a shallower part of the tailings pond and the depth to the base of the tailings was 14m (45ft). The wells were set for A, B, C, at 14m (45ft) with 3m (10ft) screen, 9m (30ft) with 1.5m (5ft) screen and at 6m (20ft) with 1.5m (5ft) screen, respectively. Each well was sand packed around the screen, sealed with bentonite above the screen, and sealed at the surface with cement. The wells were developed and purged prior to sampling.

Well cluster ETP-2 was selected to intercept the maximum tailings depth and the depth to the base of the tailings was 23 m (75ft). The wells were set for A, B, C at 23m (75ft) with a 3m (10ft) screen, at 14m (45ft) with 1.6m (5ft) screen and at 8m (25ft) with 1.6m screen, respectively. Each well was similarly completed as in ETP-1. The location of ETP-2, during the

initial reclamation often had standing water (pH 2.3 to 2.8) and in 2011, during significant precipitation events, water pools within the contoured reclamation furrows (post reclamation pH 6.5 to 7.2).

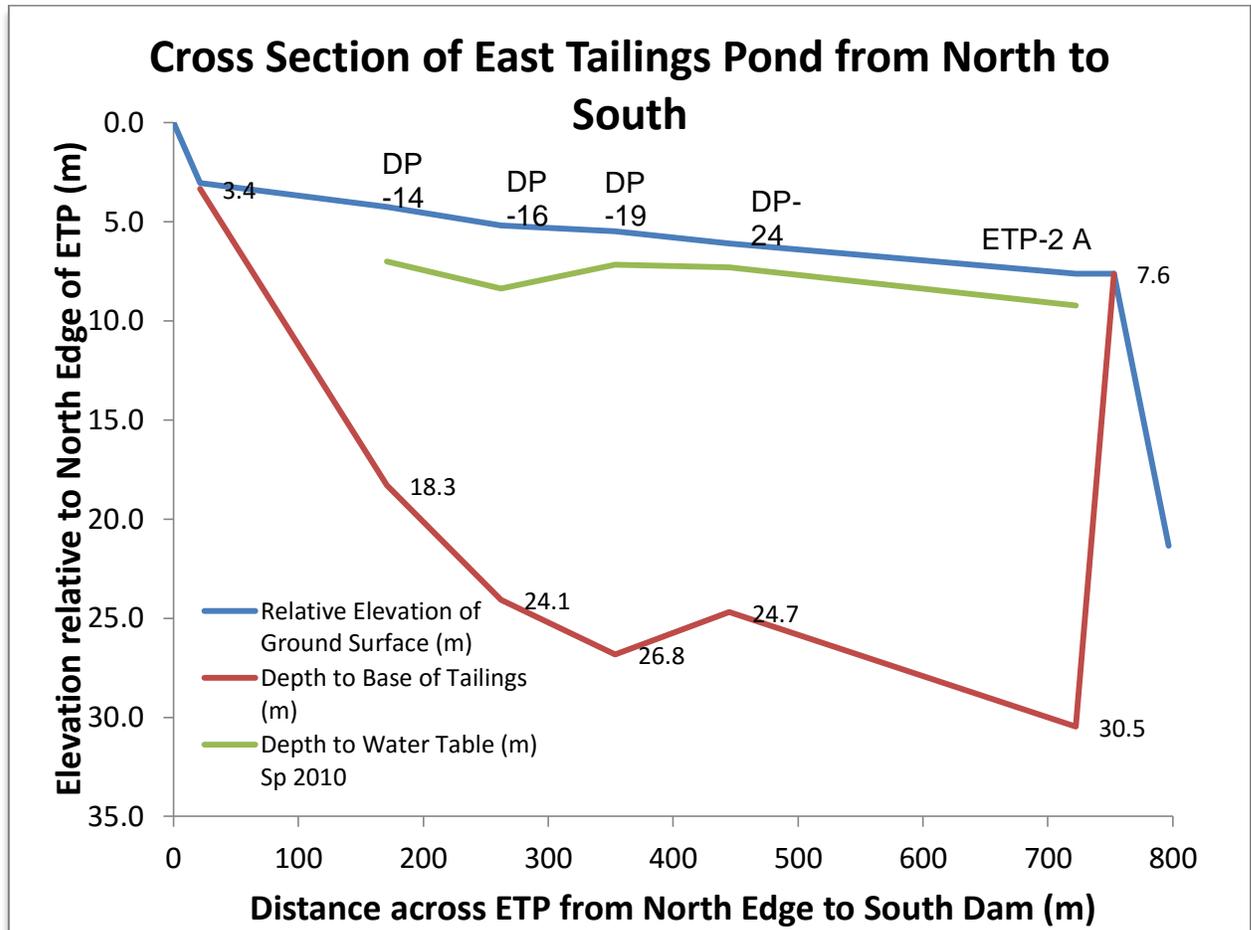


Figure 2. Cross section of East Tailings Pond showing depth of tailings, water level and surface elevation.

At approximately the same time as the installation of well clusters ETP-1 and ETP-2, seventeen borings were completed in the northern half and in western portion of the ETP. These borings were installed by direct push (DP) technology and were used to identify the depth of the interface between the tailings and the clay layer below the tailings. These borings are labeled as “DP-##” in Fig. 1.

Pyrite Pond

Reclamation Summary

The Pyrite Pond (PP) is approximately 0.8 ha (2 ac) in areal extent and is considerably smaller than the ETP. This tailings pond derived its name, apparently, from the storage of pyrite. During much of the time that the mine operated, the pyrite which was separated during the flotation process, was stockpiled and sold as a coloring agent for brown glass. At times, it has been said, there was no market for the pyrite and the stockpiled material was placed in the tailings pond with the other wastes being generated at that time. The tailings in this pond were probably discharged from pipes on the upper rim of the tailings pond and allowed to be distributed downslope. The upper and steep slope of the “pond” area has tailings depths between 0m on the northwestern slope to at least 2m (6ft) of tailings covering the northeast slope. Below the tailings containment area, the dam, which holds the tailings in place, is constructed from on site soils and clays and is approximately 10 to 12m (30-35ft) in height. Seeps through the dam face were captured in a sediment basin and transported via gravity flow lines to the central treatment facility.

The pond surface was reclaimed in 1992 using an impermeable plastic liner. Plastic sheets were spread over the tailings, which supported no vegetation, and on the southeast side, a trench approximately 0.6m (2ft) deep was excavated and the liner terminated in the trench and the trench backfilled. A thin veneer of soil (0.3m) was placed over the plastic covering the tailings pond and seeded with grasses. (E.R. Dotson, 1999, personal communication). After three years, the predominant, albeit sparse, vegetative cover was weeping lovegrass (*Eragrostis curvula*).

During the reclamation of the flat surface of the tailings pond in 1992, the upper slope was not reclaimed and the tailings remained exposed, were subject to erosion and gully formation, and washed to the surface of the Pyrite Pond. These tailings were sampled, tested by kinetic leaching studies, and determined to be a source of acid production. The slope tailings were treated in 1998 by applying two thin veneer coatings of “lime slurry,” a slurried CaO generated as a byproduct from acetylene production. The first slurry was applied 0.5-1 cm thick. The gullies were then filled using small bulldozer equipment with a mixture of clay and tailings and a second, similar veneer applied. The slopes of the pond were then covered with approximately 0.5m clayey soil and an additional 0.3m of soil was distributed over the surface of the tailing

pond membrane. Both the slopes and Pyrite Pond surface were fertilized and seeded with grasses and legumes. Currently, approximately ¼ of the surface is forested.

Hydrologic study

In 1999, to address seeps and other factors within the drainage basin of the PP, fifteen wells were drilled within the basin. Of the 15, three were within the tailings pond (PP-12, PP-13 and PP-16), one hydraulically upgradient (PP-17) and another in undisturbed rock south of the pond (PP-11). Because these were drilled for various purposes, of the wells within the tailings pond, PP-12 was completed within the tailings while PP-13 and -16, were deeper and may have extended below the tailings into the clay/tailings interface. Well PP-12 was completed to 10.6m (32ft) bgs, PP-13 to 23.4m (72 ft) bgs, and PP-16 to 26.1m (79ft) bgs. Each well was completed with a 5 cm (2in) diameter PVC piping with 1.6m screen at the base of the hole, sand packing around the screen, bentonite layer above the screened interval, filled to the surface, top 1m completed with bentonite and a concrete pad. The well logs from Wells 13 and 16 indicate that tailings were present as deep as 35m (105ft) bgs.

In the Spring of 2010, two additional borings (DP-1 and -2) were completed in the tailings pond to provide additional data on the depth of the tailings within the pond and depths to saturation. The locations of the wells and borings are shown in Fig. 3 and cross sections of the PP are shown in Fig. 4A and 4B. Figure 4A represents the data from the southeastern side and the most shallow borings while 4B shows both the deeper wells as well as the shallow borings.

As depicted in Fig. 4A and 4B, the impermeable liner may allow some seepage of surface water and ground water, especially from the upslope direction. Even with the liner covered on the edge with a trench 0.6m (2ft) deep, this may not prevent water flowing at the interface of the tailings and the base slope from entering beneath the liner and continuing to feed the tailings. The amount of direct precipitation infiltration over the 0.8 ha (2a), however, may have been substantially diminished.

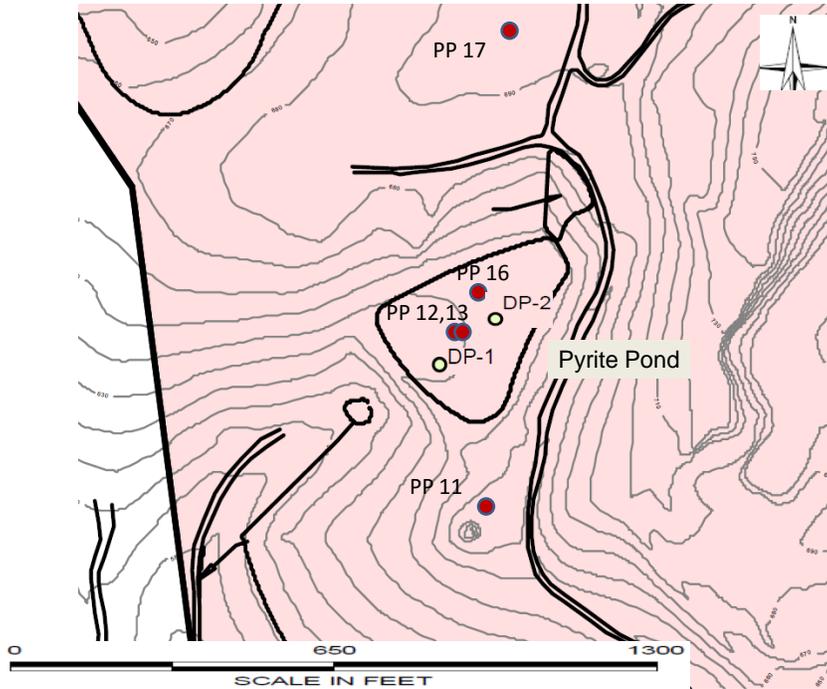


Figure 3. Topographic map of Pyrite Pond tailings pond and locations of wells and borings.

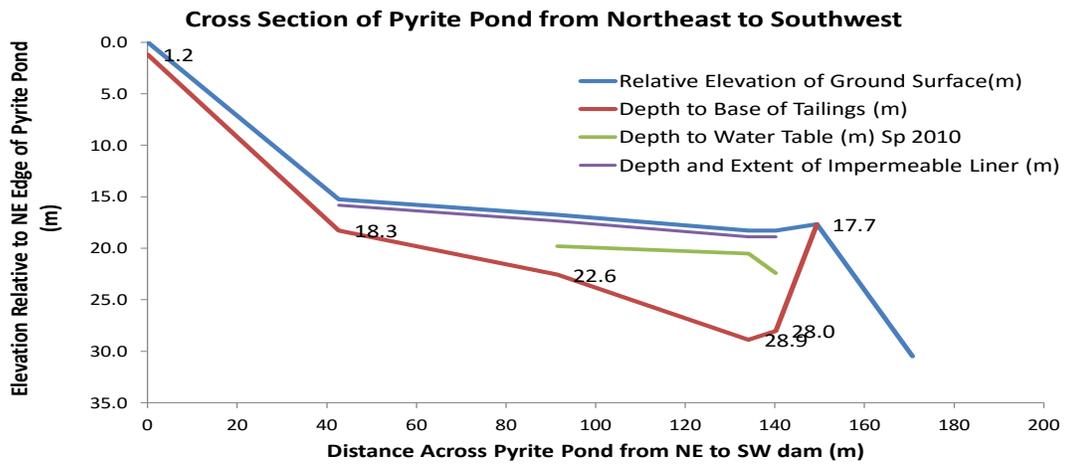


Figure 4A. Cross section of Pyrite Pond from NE to below dam to SW, based on DP-1, DP-2, and PP-12 through the eastern side of the tailings pond.

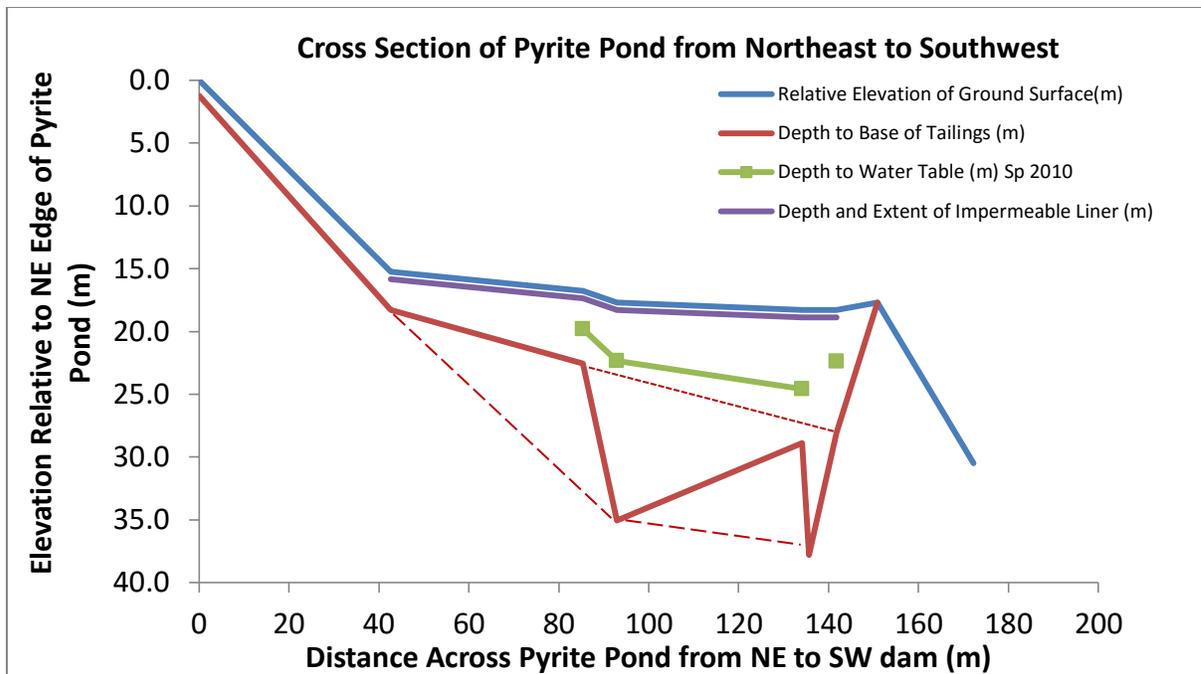


Figure 4B. Cross section of Pyrite Pond. (dotted lines are data from southeastern side of pond and dashed line represents data from center of pond)

Results and Discussion

Water level measurement data and periodic water quality samples have been collected from the wells since their installation. Rainfall is monitored daily in a manual volume collecting gage and the volume, as well as pH and specific conductance, are measured. For this study which is primarily related to interstitial and groundwater, the rainfall has been plotted as monthly and annual totals. In as much as infiltration is more likely related to longer term averages of precipitation now that the surfaces of the tailings ponds have been reclaimed and the runoff component is less flashy, the monthly totals provide a mechanism to compare whether changes in water level elevations are related to precipitation events.

East Tailings Pond.

The water level measurements from the two well sets compare the potentiometric surfaces from two depths of tailings, (shallow and deep) and also compare the water level variations with time and precipitation. Water levels were measured to within 0.15cm. The Well set ETP-1 A, B,

C (to depths of 14, 9 and 6m) was sampled intermittently between 2010 and 2012. The variations in water elevations are presented in Fig. 5.

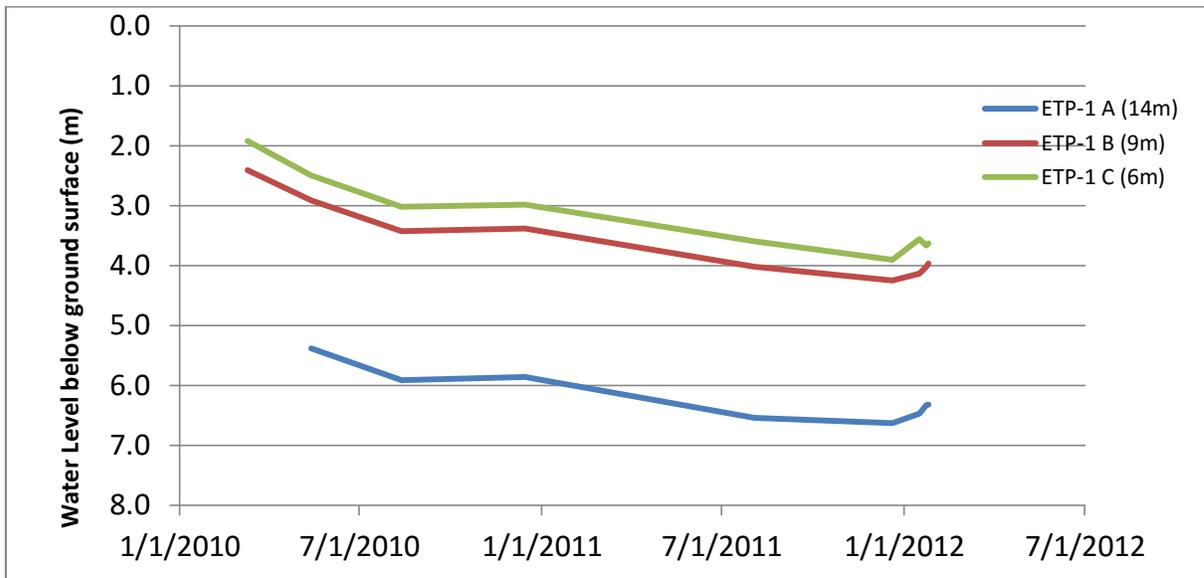


Figure 5. Depth to water level (bgs (m)) in ETP-1 A, B, and C.

Because these wells were screened and completed at 3m and 1.6m intervals from the base of the hole, the variation in water level elevation is a reflection of the potentiometric surface at that location. Therefore, while each of the wells has a very similar trend ($R^2 > 0.95$ between each set of values), the levels reflect the water pressure at that point. Given the relatively shallow nature of the tailings (14 to 6m) the differences suggest that the tailing deposition process and the fine nature of the tailings allow for stratification and that a number of perched layers may exist within the tailings. Well ETP-1 C, completed and screened from 4.5 to 6 m and, therefore, closest to the surface, most likely reflects the water table.

The water level variations were compared to rainfall during a similar time period and it appears that a delay exists between rainfall events and increases in water level, even in the shallower (ETP-1 C) well. Based on the late 2010 data and Dec 2011/Jan 2012 data, the delay may be on the order of 3 to 4 months. Figure 6 provides rainfall data during this time period. Specifically, the beginning increases in water levels in late December 2011 and January 2012 most likely relate to higher rainfall during October 2011. This delay is most likely attributed to the infiltration through soil moisture and to the water table, however, given the location of the

tailings pond within a natural discharge area, the increase may also reflect increases in base flow as a result of the higher rainfall.

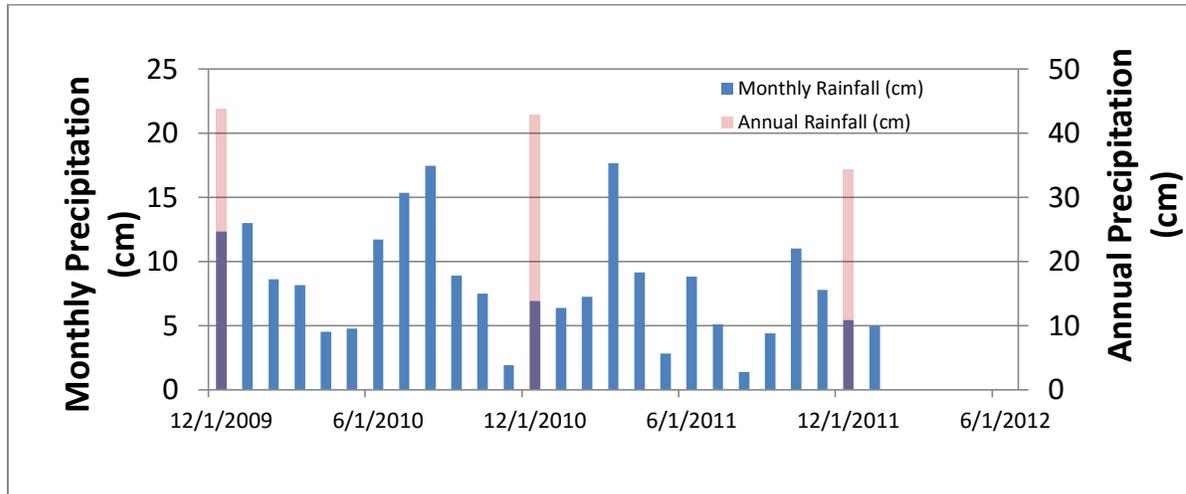


Figure 6. Monthly and annual rainfall at the Graves Mountain site.

As shown in Fig. 7, the ETP-2 A, B, C wells exhibited much less variation in water levels when compared to the shallower well set, ETP-1. Similarly, the deepest well also showed the greatest depth of water, albeit much less difference than in the shallow wells.

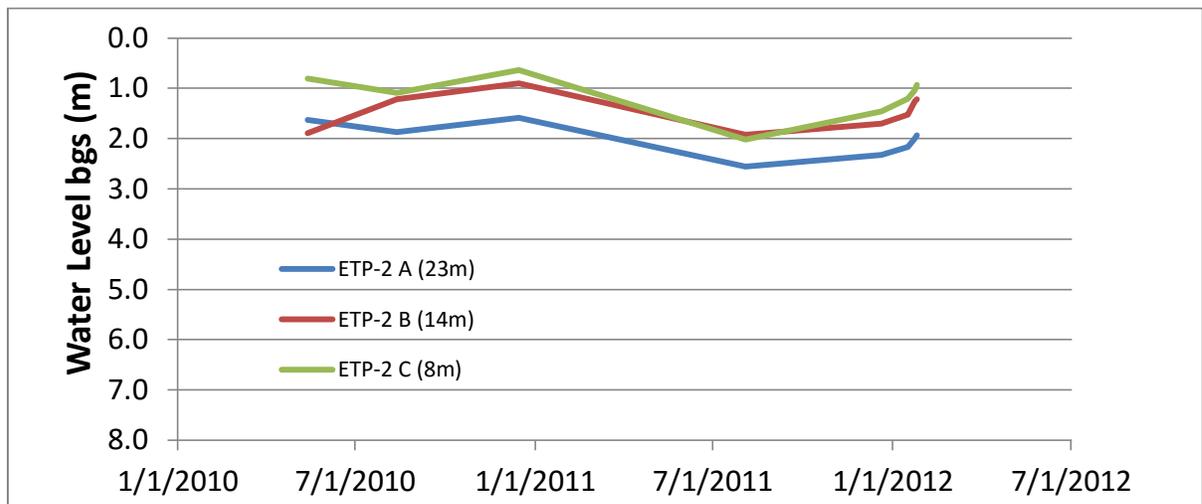


Figure 7. Depth to water level (bgs (m)) in ETP-2 A, B, and C.

These wells also exhibit a similar increase in water levels in late 2011 as seen in ETP-1 wells, although the increases elevate the water levels to nearly the 2010 data, while the elevations in ETP-1 are still significantly below the 2010 water level measurements. This is

consistent with the initial peizometer data in the vicinity of ETP-1, which indicated a steady decline in water levels in 2003 to 2005 when the near surface (1.2m bgs) peizometers no longer had measurable water levels. Assuming a long term steady water level decline in the near surface horizons, the decline from 1m bgs in 2003 to greater than 1.2 m in 2005 to nearly 4m bgs in 2012 suggests a long term trend of decreasing water levels in a shallower portion of the ETP. Given that the area in which ETP-2 was installed has been subject to surface ponding, coupled with the permeable ridge and furrow reclamation, it was assumed that the surface water was an expression of the water table. However, given that the screened intervals suggest a water level below the surface of the tailings pond, coupled with a lack of saturated conditions immediately below the ground surface when the ETP-2 wells were installed; this suggests that the surface ponding merely reflects the low percolation rates of the surface reclaimed tailings. These delays in water level fluctuations, even though water levels are within 1m of the surface, again suggest that the base flow component may be an important element determining water level elevations within the tailings.

Pyrite Pond

Water level measurements from the wells in the Pyrite Pond sub-drainage basin have been intermittently collected since 1999. Measurements from Wells PP-11 and PP-17 represent water levels in sections of the site which were not mined. Well PP-11, is located south of the Pyrite Pond and was drilled into undisturbed quartzite to a depth of 25 m (81ft), the depth at which water was first encountered, but which quickly rose in the well bore to approximately 12m below ground surface (bgs). Well PP-17 is located on the drainage divide between the Pyrite Pond water shed and the watershed draining towards the north. The well was drilled to 61.3 m (200ft) at which depth water was first encountered. The wells were developed and purged. The water levels in the wells, representing the potentiometric surface of the screened interval (the bottom 1.6m (5ft)), have been monitored and the data are presented in Fig. 8. The wells generally show increased water levels in 2003 and decreasing water levels since then with the exception of PP-17 which indicates a slight increase in recent years. Well PP-11 exhibits the greatest variation in water levels and suggests that the rock may be fractured.

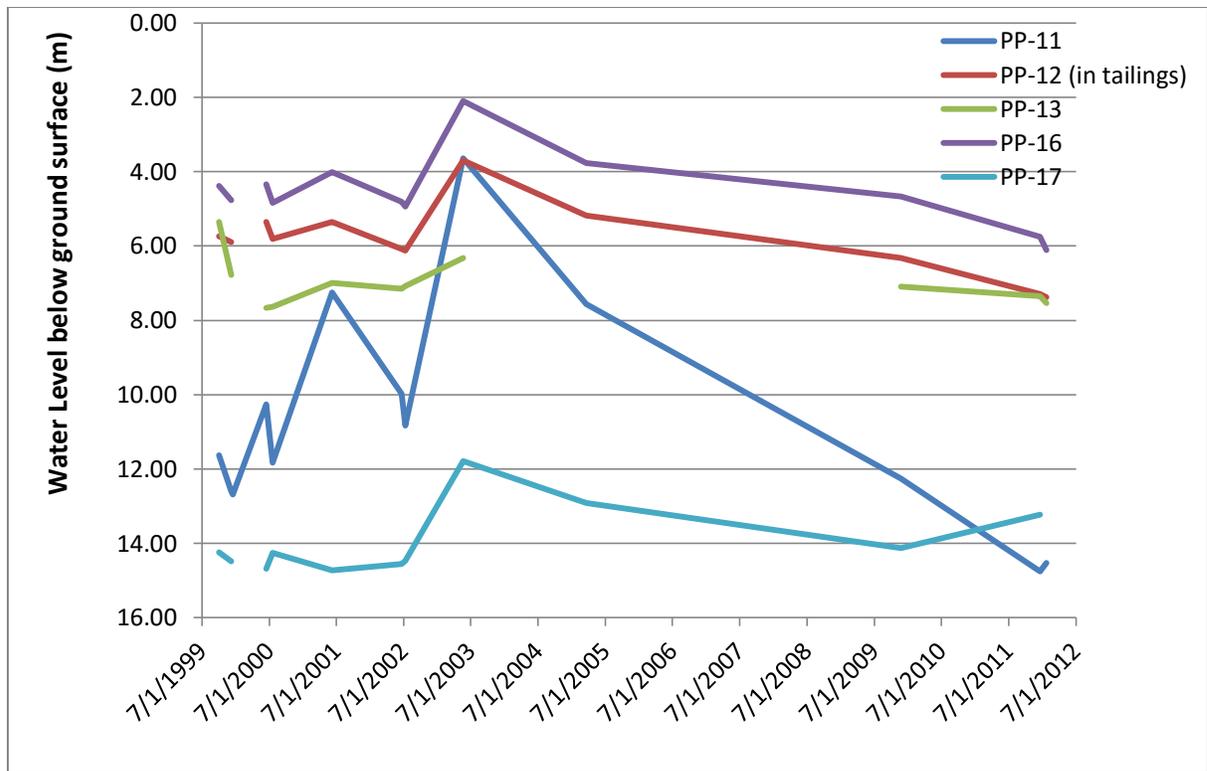


Figure 8. Water level measurements of Pyrite Pond wells.

Comparing rainfall data in Fig. 9 with PP-11, suggests that ground water elevations at this location respond to precipitation. Due to PP-17’s depth, it appears to respond more slowly and subtly to precipitation events, however, it responded to the increased precipitation in 2003 as did the others.

Wells PP-11 and PP-17, provide background against which changes in water levels within the tailings pond can be evaluated. The similarity in water levels elevations between PP-12 and PP-16 is striking; although there is an average percent difference between PP-12 and 16 of 23%, a strong relationship exists between the water levels in the two wells ($R^2 = 0.9538$). Well PP-13 had difficulties during drilling and installation and the screen may have become clogged with bentonite. Although the well was pumped and multiple attempts were made to develop it, white clay continues to be discharged during pumping and may impact water levels as well. However, PP-12 and PP-13 are in close proximity (about 3m apart) and the well casings are surrounded by water which is consistently 10 to 20 cm in depth even during very dry periods. The water levels in the wells, however, do not reflect water at the surface which reinforces the integrity of the

impermeable liner to prevent surface inflow. Given the concerns with PP-13, while the water levels are provided in the figure, they were not used in this study.

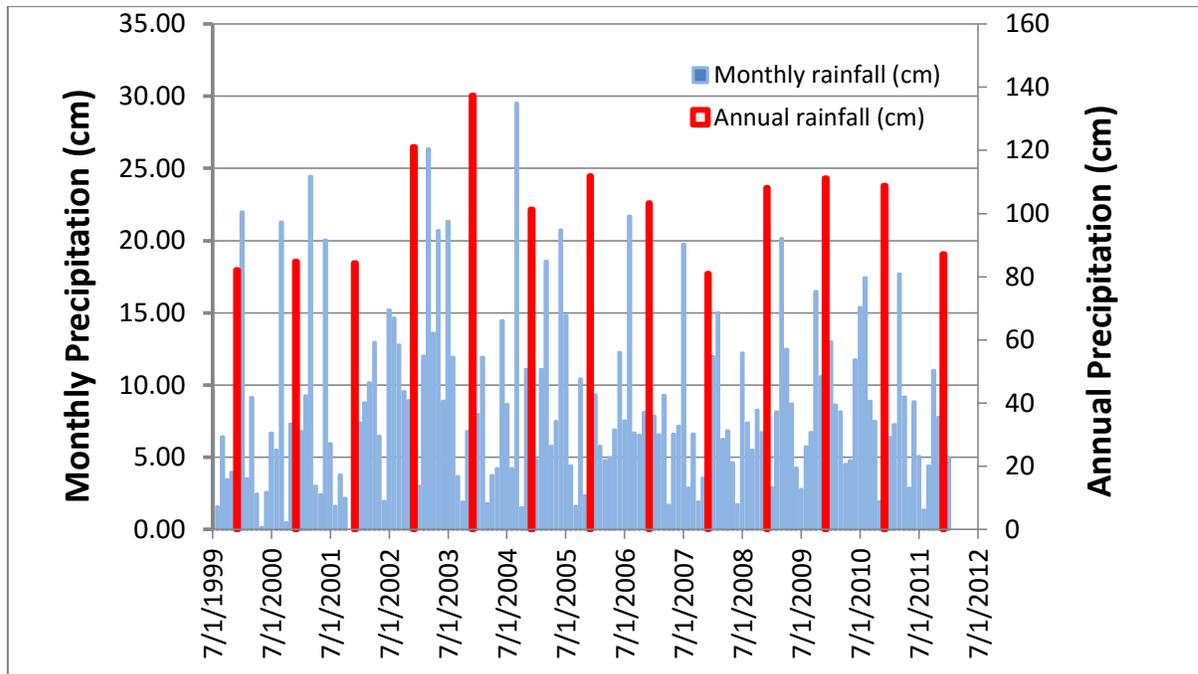


Figure 9. Rainfall at the Graves Mountain site from 1999 to 2012.

These data suggest that the liner does not completely isolate the tailings from precipitation events given the increase in the water level in 2003. The response is not as flashy as that associated with PP-11 in the surrounding bedrock, but is similar to the level of response shown by PP-17 suggesting that the tailings pond is influenced by a ground water component. This would be consistent with the location of the tailings in a natural discharge area and the inability of a surface liner to be able to address and intercept the base flow component. While the liner appears to minimize the impact of surface infiltration, the upslope dam with 1-1.6m of tailings on the surface provides a direct avenue for surface infiltration although this has most likely been somewhat moderated by the clay layer and vegetation now established on the slope. This limited surface infiltration most likely accounts for the variation in water depth of only 4m, while PP-11 had a variation in excess of 11m and was drilled to nearly the same depth as PP-16.

Summary and Conclusions

This study evaluates the hydrologic characteristics and suggests the major influence on the hydrologic parameters between two kyanite ore process tailings ponds which were reclaimed

with different reclamation strategies; one reclaimed with an impermeable plastic liner membrane and the other with an open, surface reconfiguration methodology. The Pyrite Pond (PP) was constructed and filled during the 1960's and early 1970's. In early 1992, the PP was capped with a plastic membrane, covered with a thin (0.3m) soil veneer and vegetated. In 1998, the upslope was reclaimed with an application of a calcium based alkaline slurry, covered with 1m of soil and the entire tailings pond area revegetated. The East Tailings Pond (ETP) was constructed and filled in the 1970's and early 1980's and reclaimed in 1995-96 by surface reconfiguration and the addition of soil amendments (straw, fertilizer and fine grained limestone). Piezometers and wells were installed into the two tailings ponds and also in close proximity to the PP. While the initial study was aimed at a comparison of the two reclamation strategies, the results of the evaluation of the potentiometric surface data for varying depths within each tailings pond indicate that while both tailings ponds exhibit delayed response to precipitation events suggesting infiltration effects, the delay in the ETP deep wells and PP wells could not be adequately described by a surface infiltration model. Further consideration of the surrounding well data, coupled with the tailings cross sections and water levels, suggest that the hydrologic characteristics of both tailings ponds are significantly influenced by base flow infiltration and ground water seepage into the upgradient areas of the tailings ponds.

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