Performance of Shallow Water Covers on Pyritic Uranium Tailings

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ABSTRACT

The performance of *in situ,* shallow water covers in controlling acid generation was evaluated at four recently decommissioned pyritic uranium tailings sites at Elliot Lake, Ontario, Canada. The tailings are acid generating, having a pyrite content of approximately five to ten per cent and a very low to non-existent alkaline buffering capacity.

Adverse market conditions led to the closure of all operating uranium mines in the early- to mid-1990s, followed by rehabilitation and decommissioning of mine and waste management facilities. In order to control acidic drainage, all new and active tailings areas at Denison, Quirke, Panel, Spanish-American and Stanleigh mine sites were re-engineered to provide *in situ* submersion of these tailings under shallow water covers. The tailings impoundment dams were upgraded and reinforced or in some cases reconstructed, to minimise seepages and provide a minimum 1 m depth of water cover.

With the exception of Stanleigh mine, which was closed in 1996 and rehabilitated during the late-1990s, the water covered Tailings Management Areas (TMAs) at other sites have been in operation for a period of six to nine years. The surface water quality at these sites is maintained at near neutral pH conditions by periodic addition of lime slurry to the established water covers. Additional treatment of effluent is provided as required to meet the discharge water quality standards.

The performance of the established water covers at the sites was evaluated by analysing the annual equivalent limestone consumption data. The results were compared with the performance of an older, decommissioned Nordic TMA, which was rehabilitated using revegetation techniques. The water covers at these sites are performing as designed and acid generation has been reduced to low levels. Based on the total amount of yearly equivalent limestone required to maintain water quality in the water cover and at the effluent treatment plant, it is concluded that acid generation rate at the Denison TMA has reduced to less than 0.15 per cent of its pre-water cover conditions during normal operation and rehabilitation periods. In comparison to the revegetated Nordic TMA, the acid generation rates at Denison and Panel TMAs have decreased to less than 1.6 per cent of that at the Nordic TMA. The acid generation rate at the Quirke TMA was comparable or only slightly lower than that at the Nordic TMA because of its unique terraced cell configuration, having tailings in five hydraulically interconnected cells at different elevations. Historic acidity and oxidation reaction products, accumulated during normal operating and pre-water cover periods, are flushing from upstream locations to downstream cells, thus requiring much higher equivalent limestone additions for acid neutralisation and effluent treatment.

INTRODUCTION

The Elliot Lake-Blind River region of north-central Ontario, Canada, was a major uranium-producing district during the 1950s to 1980s. Adverse uranium market conditions and low ore grade led to the closure of all uranium mines in the region, the last four main operating mines closed during the early- to mid-1990s. The ore mined in the area was low grade, containing approximately 0.1 per cent U, 0.02 - 0.2 per cent Th, 0.05 per cent rare earths, Y, Ce, and Nd, five to ten per cent pyrite and trace amounts of other metal sulfides.

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The ore was hosted as metamorphosed quartz-pebble conglomerate with the mineralisation confined mainly to the cementing material that bound the pebbles. The uranium milling and extraction processes consisted of hot-sulfuric-acid leaching, using compressed air or hydrogen peroxide as an oxidant, followed by ion-exchange separation and precipitation as ammonium di-uranate or magnesium uranate (yellow cake). The latter process was adopted for newer second-generation mills for decreasing the total ammonia load to the environment.

The tailings were neutralised and deposited in surface-based overland tailings impoundments. The Tailings Management Areas (TMAs) were generally located in valley depressions bounded by upland ridges and outcrops and impounded by cross-valley and/or other perimeter dams.

The tailings are highly acid generating and have very little to negligible alkaline buffering capacity. In the past, during the late-1960s to 1970s, the inactive tailings areas were rehabilitated and reclaimed by direct revegetation techniques, by neutralising the surface of the exposed tailings with lime or limestone, incorporation of fertilizer and vegetating the surface with agronomical species of grasses and legumes. The surface reclamation of inactive tailings has been very successful in controlling the surface erosion and improving the site aesthetics to blend with the surrounding natural habitat. However, the anticipated benefits of controlling acid mine drainage (AMD) with the established vegetation cover have not materialised at most sites (Veldhuizen *et al,* 1987). Acidic drainage continues at these sites, requiring long-term effluent collection and treatment, with the added requirements of sludge handling and disposal.

Acid mine drainage from pyritic uranium tailings has been a major environmental concern at Elliot Lake. Although the leaching and migration of uranium and thorium decay series radionuclides, present in the tailings in trace quantities, is also of concern in the long-term, its impact on the environment is small in comparison to that of the AMD (SENES 1993; SENES 1995). Thus for all newer mines that closed during the early- to mid-1990s, the tailings or waste management areas have been rehabilitated and decommissioned with *in situ*, shallow water covers. For the pyritic uranium tailings, a water cover not only provides the required acid generation control, but it also controls and attenuates the exhalation and release of the radioactive radon gas and its progeny, as well provides the shielding for attenuating gamma and other radiations.

Water has a low oxygen solubility of approximately 8.6 mg/L at 25°C and 100 kPa, and a very low diffusion coefficient of molecular oxygen of approximately 2×10^{-9} m^2/s compared to air at approximately 285 mg/L (21 per cent v/v oxygen concentration) and approximately 1.8×10^{-5} m^2/s, respectively. Similar to molecular oxygen, the diffusion coefficient of radon in water is also about four orders of magnitude lower than that in air (Tanner, 1964). Thus, a water cover is the most natural and economical oxygen-limiting barrier available at sites where regional climatic and local geographic and topographic conditions are favourable for establishing and maintaining a water cover.

While developing the decommissioning options and the associated Environmental Impact Assessment (EIA) for the closure of the last four mines at Elliot Lake, a cost-benefit analysis of the various available decommissioning options for the long-term management of the tailings areas was undertaken. Based on this analysis, it was concluded that an *in situ* shallow water cover would provide an environmentally sound and cost effective method for controlling acid mine drainage as well as exhalation of radon gas and its progeny and radiation shine form the tailings surface (SENES, 1993; SENES, 1995; Ludgate *et al,* 2002).

For water cover requirements, Elliot Lake has a suitable temperate-continental climate, having an annual precipitation of approximately 1 m and evaporation of approximately 0.6 m, with the excess being available for run-off and infiltration. The impoundment dams of the newer tailings areas were upgraded or constructed new during the 1970s and 1980s as low permeability till-core dams, which maintain a high water table within the tailings basin (Ludgate *et al,* 2000; Payne, 2000; BHP; 2001). With some modifications, it was thus possible to provide *in situ* submersion and establishment of shallow water covers at all new tailings management areas for long-term AMD control, management and decommissioning.

Having obtained all the required approvals from the regulatory authorities, five TMAs at Denison, Quirke, Panel, Spanish-American and Stanleigh mine sites have been rehabilitated and decommissioned with shallow water covers. The first four sites were rehabilitated and decommissioned during 1992 - 1996, and the last TMA at the Stanleigh mine site, which closed in 1996, was rehabilitated and decommissioned during 1997 - 1999.

This study evaluated the performance of the established shallow water covers at these TMAs, which have been in place for the past six to nine years, except for the Stanleigh TMA which only filled to its capacity by the fall of 2002. The Stanleigh TMA was, however, operated in such a way that most of the tailings were deposited and maintained underwater during the regular mine/mill operation.

The performance of the water cover in controlling acid generation was established by obtaining and analysing the water quality and effluent treatment data, most suitably those pertaining to the total amount of equivalent lime or limestone alkalinity used at each site for controlling and maintaining the water cover at near neutral conditions and in the final effluent treatment to meet the discharge standards. The results were also compared with the equivalent lime requirements of an older revegetated Nordic TMA to establish the impact and degree of acid generation control provided by water covers at these sites.

WATER COVERED SITES

Figure 1 shows the general location of Denison, Quirke, Panel and Stanleigh mine TMAs, which have been rehabilitated with shallow, *in situ* water covers in the Elliot Lake area. The first mine was owned and operated by Denison Mines Limited and the remaining three mines were owned and operated by Rio Algom Limited (now BHP Billiton). The decommissioning plans for the first three mine sites were approved by the regulatory authorities and recommended to the Federal Government by the Federal Environmental Assessment and Review Office (FEARO) in 1996 (CEAA, 1996). The approval for the Stanleigh mine site was granted in 1998.

The rehabilitation and decommissioning of the Denison mine site started in 1993 and was completed by 1996, and that of Quirke and Panel started in 1992 and was completed by 1995 and 1993, respectively. Rehabilitation and decommissioning activities at the Stanleigh mine site started in 1997, the final dam construction at the TMA was completed by 1999 and the TMA was completely filled to the desired water level elevation by the fall of 2002. A brief description of these sites together with their rehabilitation and decommissioning activities and management practices are provided below.

Denison tailings management area

The Denison mine property is located approximately 16 km northeast of the city of Elliot Lake (Figure 1). The mine operated from 1957 to 1992 and produced approximately 63 million tones of pyritic uranium tailings containing approximately six per cent pyrite. The decommissioning activities at the site started in 1993 and were completed by 1996.

The tailings at the site were deposited in two tailings management areas, TMA-1 and TMA-2, having a combined surface area of approximately 271 ha. TMA-1 is south of TMA-2 and has an area of 235 ha containing approximately 59.5 million tones (45.8 million cubic metres) of tailings. Prior to decommissioning, TMA-2 had an area of 36.3 ha and contained approximately 3.5 million tones (2.7 million cubic metres) of tailings. The two TMAs lie within several former lake basins and are contained in a combined watershed of area 485 ha.

TMA-1 lies in a valley surrounded by east-west trending ridges and is impounded by five low permeability, engineered dams. Prior to decommissioning, the tailings basin had a partial water cover in the western part of the basin. Approximately 2.4 million tonnes (1.83 million cubic metres of tailings that were above the anticipated final water elevation were dredged and relocated (dredged by the wedge) to the deeper central and western parts of the basin to provide a minimum of 0.9 m of water cover.

TMA-2 lies in a north-west trending valley and is impounded by three low permeability, engineered dams. In order to establish a single elevation water cover in TMA-2, excess tailings, approximately 1.8 million tonnes (1.4 million cubic metres) above the anticipated water level, were removed by hydraulic monitoring and slurry pumping. The tailings were relocated to TMA-1 and to the underground workings. In order to neutralise the resident, historic acidity in the exposed and relocated tailings prior to the establishment of water covers and to provide an additional alkaline buffering capacity to counter future oxidation of the tailings, sufficient amount of lime or limestone was incorporated onto the surface of the exposed tailings as well as mixed with the relocated tailings. During this rehabilitation period although a significant amount of lime was used, it nonetheless prevented the subsequent water covers to become significantly acidic (pH <4) and decreased the neutralisation load requirements at the effluent treatment plant.

The water elevation in TMA-2 is higher than that in TMA-1 and surface water discharge flows to TMA-1. All engineered dams in the two basins were upgraded and reinforced to conform with the low permeability engineered-dam codes, and to increase their structural integrity and minimise seepage. Figure 2 shows the location of the two TMAs and an aerial view of the Denison property after decommissioning.

The water covers in the two TMAs are maintained by natural precipitation and run-off from the combined watershed. TMA-1 receives discharge flows from TMA-2 to the north and from the upstream located Spanish-American TMA, belonging to Rio Algom and also decommissioned with a shallow water cover to the south of TMA-1. The final effluent of the combined TMA facility discharges from an engineered discharge outlet at TMA-1. An effluent treatment plant near the outlet provides the necessary treatment to the discharge effluent, as and when required, for controlling pH, dissolved metals and radium. The treatment sludge is allowed to settle in a sludge settling pond downstream of TMA-1 and the final treated effluent is discharged to the receiving water of Serpent River via Stollery Lake, which is used as a secondary effluent holding and polishing basin.

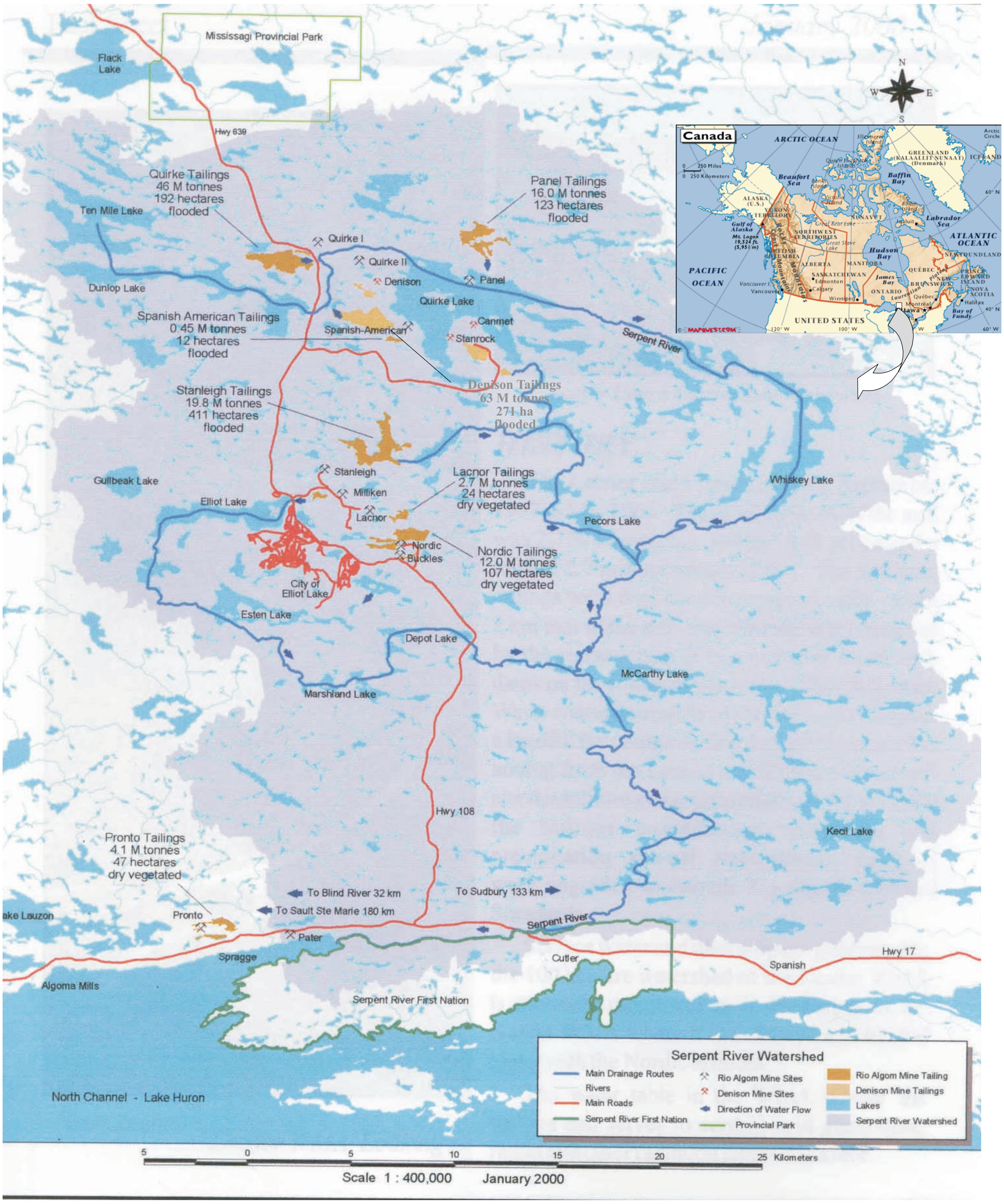

FIG 1 - Locations of the various tailings management areas in the vicinity of the city of Elliot Lake, Ontario, Canada.

The surface water quality in the two TMAs is maintained at near neutral conditions by periodical addition of hydrated lime slurry or a solution of sodium hydroxide or carbonate to the water covers. Because of this strategy and the initial neutralisation and incorporation of lime in the exposed and relocated tailings, the overall water quality in the TMAs has improved significantly since completion of the site remediation work. The entire TMA system is reaching near equilibrium conditions requiring only periodical pH adjustment, especially during spring run-off. However treatment continues to be required for controlling dissolved radium in the discharged effluent on a regular basis. The site is currently monitored and is managed on a care and maintenance basis.

Quirke tailings management area

The Quirke mine site and TMA are located approximately 14 km north of the city of Elliot Lake (Figure 1). The mine operated from 1956 to 1961 and from 1968 to 1990, and produced approximately 42 million tonnes of acid generating tailings and four million tonnes of waste rock. Rehabilitation and decommissioning activities at the mine site including establishment of a shallow water cover on the tailings started in 1992. All contaminated materials, soils and acid generating waste rock from the former mine/mill site were hauled and deposited in the tailings management area.

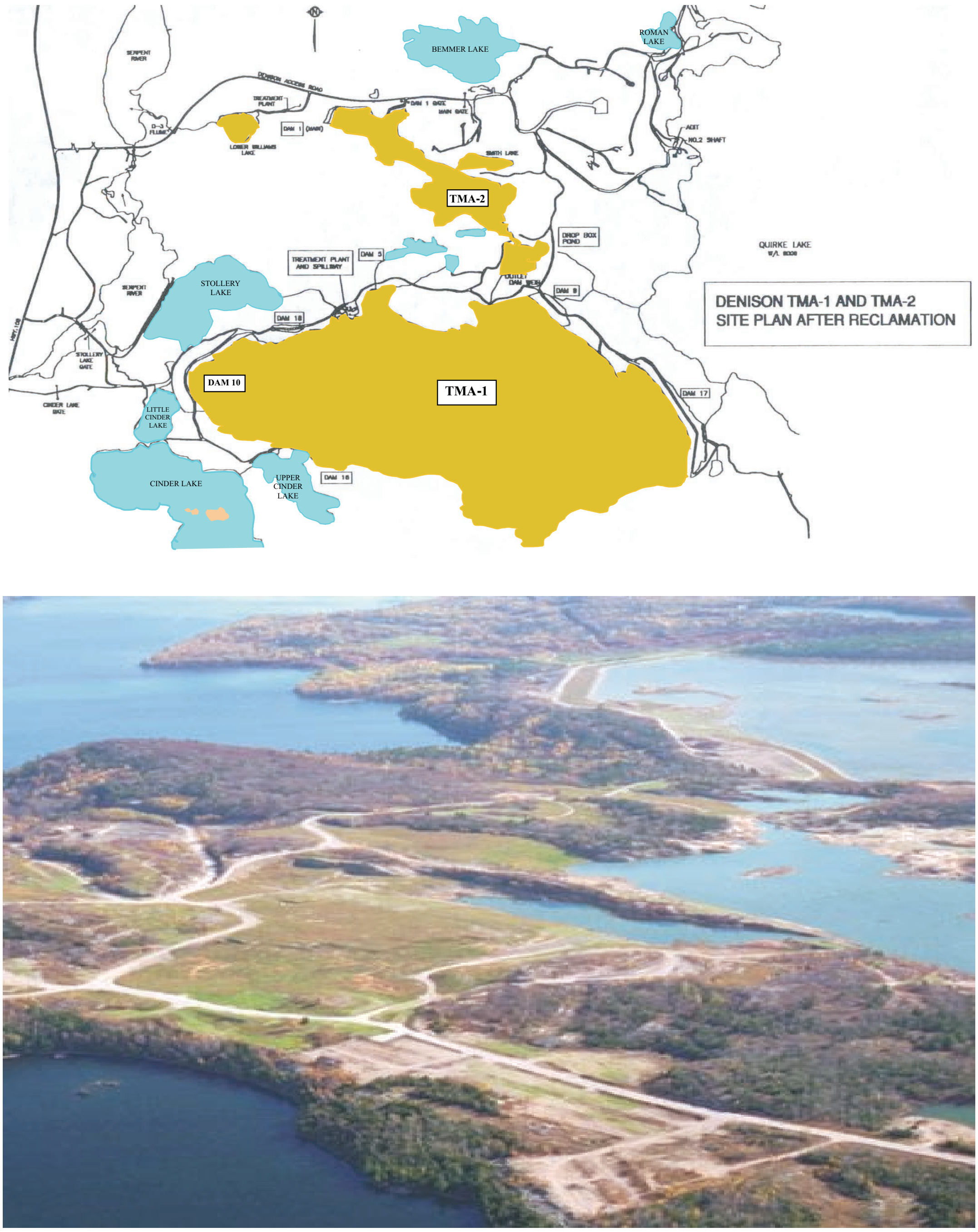

FIG 2 - General location map and an aerial view of the submerged Denison TMA.

The tailings and waste rock were placed in a 192 ha TMA, which is located in a valley containing east-west trending ridges and impounded by low permeability containment dams. The acid generating waste rock was used to construct internal haulage roads and dykes within the waste management facility. The tailings management area has an elevation difference of approximately 15 m along the east-west direction, which made it difficult to establish a single elevation water cover. The site was thus divided into five cells by internal dykes in a terraced configuration to provide the required water cover at five different elevations, as shown in Figure 3. The internal dykes have fine tailings and till layers on the upstream sides to minimise seepage losses through them. The perimeter containment dams are engineered, clay-core-earth filled dams keyed onto the grouted bedrock surface at the bottom. At the main eastside dam, where the bedrock was too deep, a vertical bentonite grout curtain was also constructed below the dam as a cut-off wall between the clay core and basement rock to minimise seepage losses (SENES, 1993; Payne, 2000; BHP, 2001).

The rehabilitation of the Quirke TMA with complete submersion of the tailings in all five cells was completed by 1995. The water cover in the TMA is maintained by natural precipitation and run-off from the catchment area of the site, and by diversion of the surface discharge flow from the upstream located Gravel Pit Lake. The water level in the Gravel Pit Lake is maintained approximately 3 m above the maximum water elevation in the TMA. This facilitates a gravity inflow from Gravel Pit Lake to the TMA, at the same time maintaining a higher hydraulic pressure head in the lake to minimise seepage of contaminated porewater from the TMA to the lake (Figure 3).

FIG 3 - General location map and an aerial view of the submerged Quirke TMA.

Prior to the establishment of the water cover, the surface of the tailings in the TMA was levelled and agriculture grade limestone was incorporated into the exposed tailings surface to neutralise existing and any potential acidity generated during and after establishment of the water cover. Hydrated lime slurry is periodically added to the various cells, as and when required, to maintain near neutral pH conditions in the surface water cover.

The water quality in the uppermost cell #14, adjacent to Gravel Pit Lake, is close to discharge quality levels, but flushing of previously accumulated acidity and oxidation reaction products is occurring from the upstream to the downstream located cells. An effluent treatment plant, located near the lowermost cell #18, provides the require treatment for controlling pH, dissolved metals and radium levels to the effluent discharged from the last cell. Presently, the site is in a transition phase of treatment, monitoring, and care and maintenance.

Panel tailings management area

The Panel mine site and TMA are located approximately 23 km to the northeast of the city of Elliot Lake (Figure 1). The mine operated initially from 1958 to 1961, and then from 1979 to 1990, producing approximately 16 million tonnes of pyritic tailings. The tailings were deposited in two bedrock rimmed basins: a north Main Basin and a South Basin, comprising the Panel TMA. The Main Basin is approximately 84 ha in area and the South Basin is approximately 39 ha, having a combined watershed drainage area of approximately 280 ha. Figure 4 shows the Panel TMA and an aerial view of the site after rehabilitation and decommissioning.

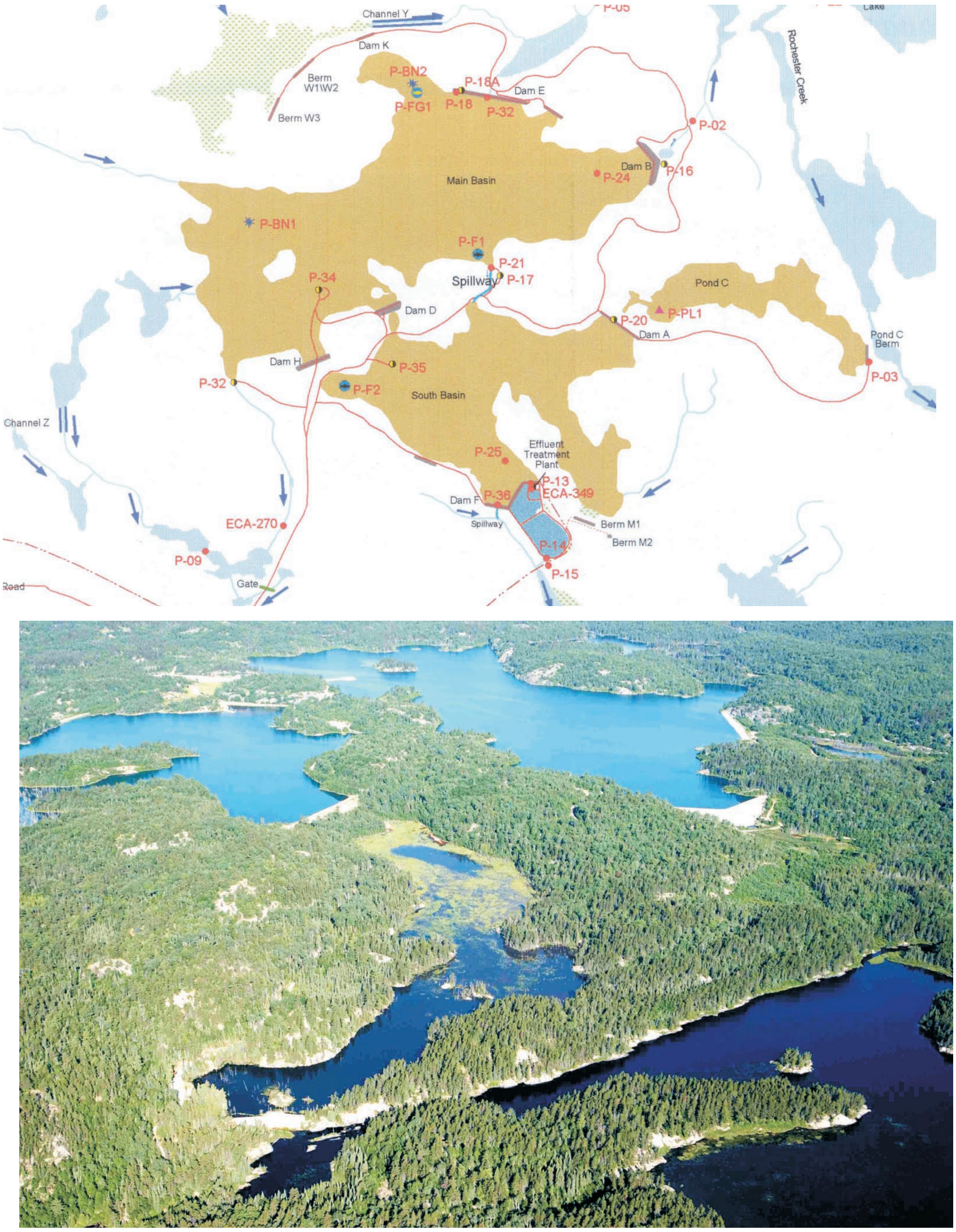

FIG 4 - General location map and an aerial view of the submerged Panel TMA.

The South Basin contains a relatively small quantity of tailings that were deposited during the late-1950s and are contained by two low permeability dams. The majority of the tailings are contained in the Main Basin, bounded within a bedrock basin, and impounded by four engineered, low permeability dams, constructed along about 15 per cent of the perimeter. Drainage from Main Basin enters South Basin via a spillway constructed in a rock rim between the two basins. During the later operating period of the Panel mine/mill and TMA, the tailings in the South Basin were always underwater and the basin was primarily used for holding and storage of the discharge effluent from the TMA for treatment purposes. The effluent treatment plant is located at the south end of the South Basin. The treated effluent is discharged via a series of three hypalon lined sludge settling and polishing ponds to the receiving water system of Quirke Lake.

The rehabilitation and decommissioning activities at the Panel TMA started in 1992 and were completed by 1993, submerging the entire basin under a minimum water depth of approximately 1 m. To facilitate a single elevation water cover in the Main Basin, excess tailings in its western section that were above the anticipated final water cover elevation were excavated and relocated by trucking to the deeper central and eastern parts of the basin. During site rehabilitation, limestone or lime was incorporated into the exposed and relocated tailings, and hydrated lime slurry was added to the water covers in the two basins to neutralise any resident and historic acidity present, as well as for providing additional alkaline buffering capacity for neutralising future acid generation within the tailings substrate. The water cover in the TMA is further maintained near neutral conditions by period addition of hydrated lime slurry to the two basins. Because of the large holding capacity available at the Panel TMA, the effluent at this site is only treated seasonally during spring and fall months.

The Panel TMA was extended in 1998 - 1999 to include a 16 ha Panel Wetland area, located to the east of South Basin in an east-west trending valley, downstream of its main dam. The Panel Wetland area contains partially submerged tailings that were deposited by accidental spillage of tailings in the late-1950s. The tailings in the wetland basin are retained and its water level maintained by an engineered dam at the outlet end to the east.

Stanleigh tailings management area

The Stanleigh mine site and tailings management area are located approximately 5 km northeast of the city of Elliot Lake (Figure 1). The Stanleigh TMA contains tailings from both Stanleigh mine and mill and from a nearby Milliken mine and mill. The Milliken mine and mill operated from 1958 to 1964, producing approximately 5.7 million tonnes of tailings. The Stanleigh mine and mill originally operated from 1957 to 1960, and then from 1983 until mine closure in mid-1996.

The TMA has a designed capacity of 71 million tonnes of tailings that would have been produced through the original planned operating period of the Stanleigh mine until 2020. The premature closure of the mine and milling facilities resulted from the cancellation of the long-term uranium delivery contracts by the Ontario Hydro utility, the sole purchaser of the mine's uranium production. The total surface area of the TMA is large at 411 ha, consisting of East, West and South Arms, as shown in Figure 5. At closure, the TMA only contained approximately 19.8 million tonnes of tailings, mostly contained within the West and South central arms of the basin.

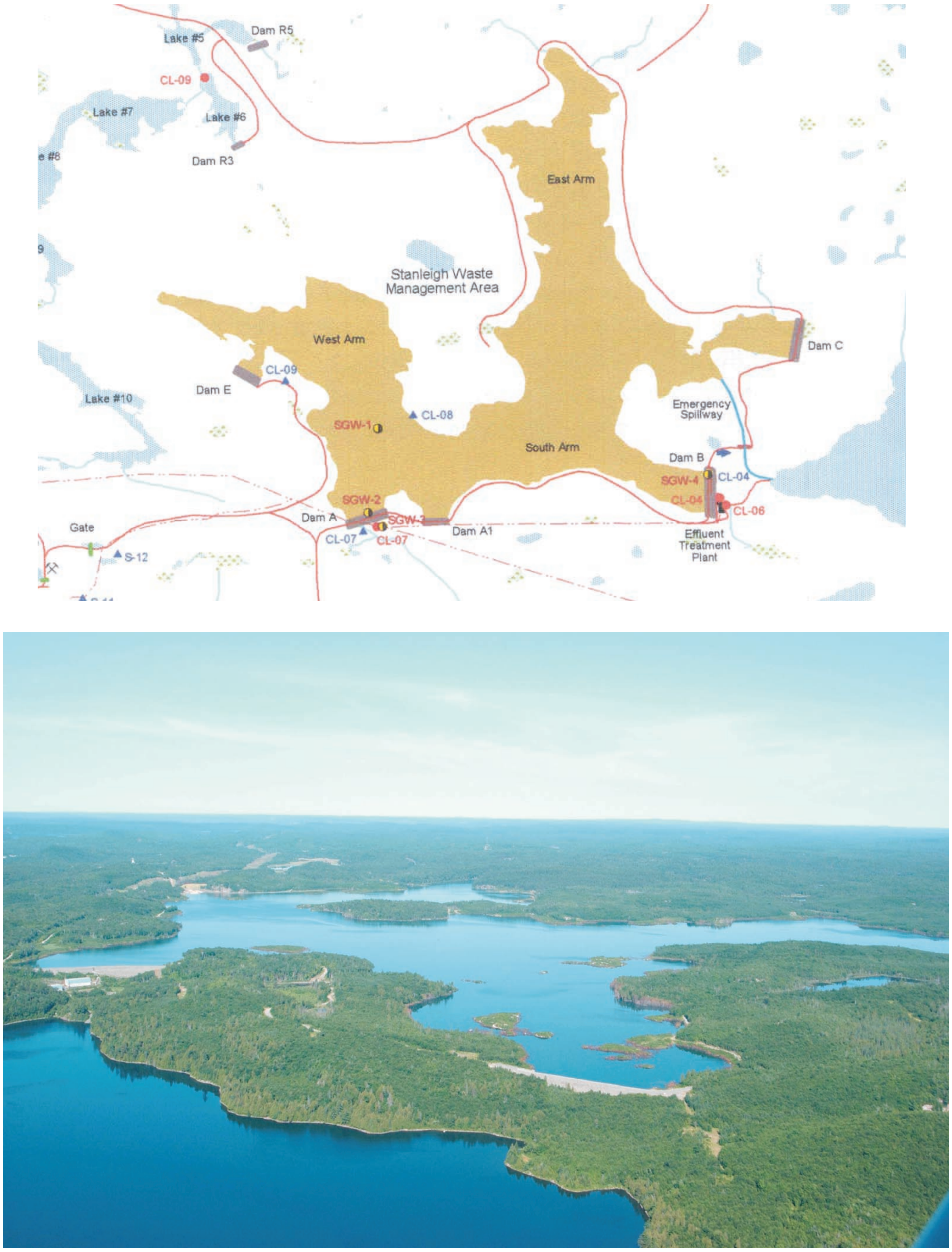

FIG 5 - General location map and an aerial view of the submerged Stanleigh TMA.

The TMA is located in several former lake basins where a majority of the tailings were deposited underwater during the latter operating period of the mine. The TMA is bounded by five engineered, low permeability dams (Figure 5). The effluent treatment plant is located on the southeastern side of the TMA. It is fully automated providing treatment for pH control, dissolved metals and radium removal, flocculation, effluent/sludge filtration and clarification.

The rehabilitation and decommissioning activities at the TMA started in 1997 and were completed by 1999 with the completion of the main dam at the southeast end of the basin, upstream of the effluent treatment plant. Tailings deposited in the West Arm section of the TMA during earlier operations of the Stanleigh and Milliken mines that were above the anticipated final water elevation in the basin were excavated and relocated to the deeper central parts of the basin in 1997. Similar to the practice followed at other TMAs, during this relocation period hydrated lime slurry was added to the basin to neutralise resident stored acidity.

Generally because of the underwater disposal of most tailings, the water cover in the Stanleigh TMA was only mildly acidic during the mine operation and thereafter, except in the high elevation areas before tailings relocation and complete submersion. Since completion of the main dam in 1999, the TMA was allowed to fill by natural precipitation and run-off from the combined catchment area of the basin, which took until the fall of 2002 for the water cover to reach the designed operating level. During this period, no effluent was discharged and the treatment plant was idle until October 2002.

The Stanleigh TMA is still under a transitional phase, progressing slowly towards the operating equilibrium conditions. The site is currently managed on a monitoring, and care and maintenance basis.

Presently, all mine and TMAs in the Elliot Lake area, including those rehabilitated previously with a vegetation cover, are managed for both mining companies by Denison Environmental Services of Elliot Lake.

PERFORMANCE OF SHALLOW WATER COVER SITES

Results and discussion

The tailings in the four TMAs are characterised as highly acid generating, having a very little to negligible alkaline buffering capacity available and a negative net neutralisation potential (NNP) of approximately -100 to -150 kg $CaCO_3$/tonne tailings. A small amount of alkalinity present in the crushed ore was quickly consumed in the acid leach process during milling. The tailings contained only minor amounts of resident alkalinity resulting from neutralisation in the mill prior to their disposal to the TMAs. The tailings are mainly comprised of quartz (up to 75 wt per cent), muscovite (10 to 12 wt per cent), potassium feldspar (5 to 10 wt per cent), pyrite (5 to 10 wt per cent); minor sericite, plagioclase, chlorite and calcite; and gypsum and metal hydroxides formed during lime neutralisation. Generally, 50 per cent of the tailings are finer than 75 µm. While the higher tailings elevation area of the TMA where the water cover is shallow contained coarser tailings, the downstream deep water cover part of the basin contained mostly fine tailings.

The total amount of tailings contained in each of the five TMAs, Denison, Quirke, Panel, Spanish-American and Stanleigh, their respective surface areas and the year following complete rehabilitation and full submersion of the tailings are given in Table 1.

TABLE 1

Total amount of tailings, their surface area and the year of complete submersion of the site following completion of rehabilitation activities for Denison, Quirke, Panel, Spanish-American and Stanleigh mine Tailings Management Areas (TMA).

Site	Total amount of tailings (million tones)	Total surface area (ha)	Year of complete submersion
Denison	63	271	1996
Quirke	46	192	1995
Panel	16	123	1993
Spanish-American	0.5	51	1994
Stanleigh	19.8	411	2002
Nordic and Lacnor	14.7	131	-

The performance of the established shallow water cover at each site was assessed by collecting and analysing the yearly data on the combined alkali additions, in terms of equivalent limestone addition to the integrated basin including the water cover and the effluent treatment plant to maintain the final effluent discharge quality. Whenever available, the equivalent lime consumption data were compiled according to pre, during and post rehabilitation periods. The performance of the water covered sites was also compared with that of a previously decommissioned Nordic TMA having a vegetation cover. The Nordic TMA has been inactive since the closure of the Nordic mine in 1968. The TMA was rehabilitated during the mid- to late-1970s using surface revegetation techniques and is managed on a continuous effluent collection and treatment basis. Pertinent data for the Nordic TMA are also provided in Table 1.

The performance of the established water cover in the TMA could not be judged from its water quality in the surface water cover and that of the influent water to the effluent treatment plant, as the added lime or other alkali during and post rehabilitation periods has a certain modifying effect on the water quality in the basin, and to a certain extent on the rate of acid generation/neutralisation.

The most comprehensive alkali addition data are available for the Denison TMA, including its last operating period from 1990 to 1992, during site rehabilitation from 1993 to 1996 and post rehabilitation period to date. Table 2, gives the yearly equivalent limestone added to the combined basin to maintain its integrated discharge water quality. For performance evaluation and

TABLE 2

Yearly equivalent total limestone addition (total and area normalised) to the Denison TMA.

Year	Total $CaCO_3$ equivalent (tonnes/year)	Total $CaCO_3$ equivalent (tonnes/ha/year)
1990	42 779	157.858
1991	52 119	192.320
1992	6636	24.487
1993	3201	11.813
1994	10 288	37.963
1995	9024	33.300
1996	74	0.275
1997	59	0.218
1998	18	0.065
1999	1	0.002
2000	1	0.002
2001	2	0.006
2002	0.16	0.001

comparison amongst sites, the equivalent limestone data were further normalised to the unit area of the site to obtain equivalent limestone addition per ha per year.

The performance of the Denison TMA, during pre to post rehabilitation period is shown in Figure 6. The data clearly show a significant reduction in the yearly equivalent limestone consumption, hence acid generation, from approximately 150 - 200 tonnes $CaCO_3$ equivalent/ha/year during 1990 - 1992, to less than 40 tonnes $CaCO_3$ equivalent/ha/year during the 1993 - 1996 rehabilitation period and less than 0.05 tonnes $CaCO_3$ equivalent/ha/year during the post rehabilitation period of 1997 - 2002. During the post rehabilitation and on-going maintenance period, the equivalent limestone consumption rate has decreased to less 0.03 per cent and 0.15 per cent, respectively, of those during operating and rehabilitation periods. It should, however, be mentioned that during the normal operation of the mine/mill and waste management facilities, a greater volume of the effluent was treated and discharged from the TMA, hence the equivalent limestone requirements were also high.

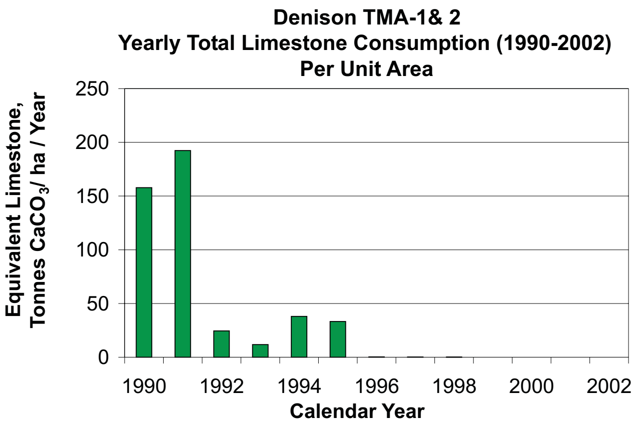

FIG 6 - Area normalised, annual-equivalent-limestone consumption rate for the Denison TMA.

For all other TMAs, excellent lime usage data are available for the post rehabilitation period from 1998 and onwards. The yearly equivalent limestone usage data for the various sites, including that of Nordic TMA, are given Table 3. A comparative performance of the water covered sites with that of the revegetated Nordic TMA are given in Figure 7.

TABLE 3

Yearly average equivalent-total-limestone addition, total and area normalised, to Denison, Quirke, Panel, Stanleigh and Nordic TMA, for the period 1998 - 2001.

Site	Total $CaCO_3$ equivalent (tonnes/year)	Total $CaCO_3$ equivalent (tonnes/ha/year)
Denison	5.07	0.019
Quirke	1405.40	7.320
Panel	15.54	0.126
Stanleigh	0.68	0.002
Nordic	1117.91	8.534

The Nordic TMA has been inactive since 1968 and fully remediated with a well-developed and established vegetation cover since the late-1970s. The tailings above the water table at this site are under unsaturated conditions, where active acid generation and AMD continues unabated. Although the rate of acid generation at the site has decreased steadily over the post-decommissioning period (BHP, 2001), the equivalent limestone consumption rate at this site is still the highest at approximately 8.5 tonnes $CaCO_3$ equivalent/ha/year (Figure 7). In comparison to the Nordic TMA, the equivalent limestone consumption rates for the water covered Panel, Denison and Stanleigh TMAs are low at 0.13, 0.02 and 0.002 tonnes $CaCO_3$ equivalent/ha/year, respectively, and comparable for the Quirke TMA at approximately 7.3 tonnes $CaCO_3$ equivalent/ha/year.

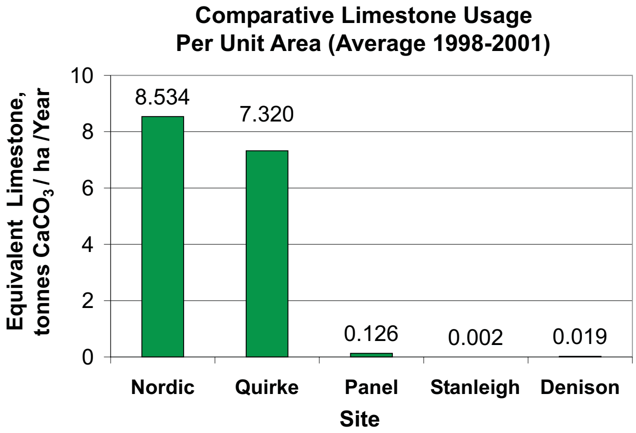

FIG 7 - Area normalised, annual-equivalent-limestone consumption rates for Nordic, Quirke, Panel, Stanleigh and Denison TMAs.

The Denison and Panel TMAs have two separate basins, which are self contained within bedrock rims or valley ridges and outcrops. Although, water elevations in their respective basins are at different levels, they are hydraulically linked only through their surface water outflows. With the established water covers and surface alkali amendments, both during and post rehabilitation periods, the post-rehabilitation acid generation rate in these TMAs has decreased to less than 1.5 per cent of that at the revegetated Nordic TMA during the same period. The acid generation rate in the Stanleigh TMA is even lower, although the site has yet to attain its post-rehabilitation equilibrium level. Because a majority of the tailings in the Stanleigh TMA were deposited and managed underwater, the overall lime consumption and acid generation rates are lower compared to other sites.

The post rehabilitation lime consumption rate at the Quirke TMA is comparable or only slightly lower than that at the Nordic TMA, at 7.3 and 8.5 tonnes $CaCO_3$ equivalent/ha/year, respectively. This is not surprising given the unique rehabilitation of the Quirke TMA as five hydraulically interconnected cells in a terraced configuration to offset the elevation difference at the site. The cells are separated by internal dykes constructed of waste rock and tailings, having fine tailings and till blankets on the upstream sides to minimise seepage losses through them. The water levels in individual cells are maintained at different but lower elevations along the down gradient slope. Because of this hydraulic interconnection and down gradient slope, a significant flow occurs from upstream to downstream cells, requiring augmentation of the water cover in the uppermost cell from other water bodies.

This groundwater flow through the cells in the Quirke TMA is also causing flushing and transportation of the resident, historic acidity that was accumulated during mine operation and pre-rehabilitation periods from the upstream to the downstream cells. Thus, the equivalent total limestone requirement at this site is significantly higher than at other water covered sites, and would continue to remain high until all the resident acidity and stored oxidation reaction products from its previous exposure history are completely flushed out. With the continued flushing of these historic products, the performance of the Quirke TMA is gradually expected to approach those of the Denison and Panel TMAs. However, it is still premature to estimate the required time frame for the anticipated performance improvement.

SUMMARY AND CONCLUSIONS

Five tailings management areas containing acid generating pyritic uranium tailings at Denison, Quirke, Panel, Spanish-American and Stanleigh mine sites at Elliot Lake, Ontario, Canada, have been rehabilitated and decommissioned with *in situ*, shallow water covers. The first three mine closed in 1990 - 1992 and their TMAs were rehabilitated during 1992 - 1996. The last, Stanleigh mine, closed in 1996, and its TMA was rehabilitated by 1999 and filled to the desired water elevation by the fall of 2002.

The performance of the established shallow water covers at these sites was evaluated by analysing their annual lime consumption data for the total equivalent limestone alkalinity used at each site for acid neutralisation in the established water cover and at the effluent treatment plant to meet the integrated, effluent-water-quality discharge standards. The performance results were also compared with that of an older, vegetatively rehabilitated Nordic TMA, which has been inactive since 1968 and rehabilitated during the late-1970s.

Based on the annual equivalent limestone consumption rate, the established water cover at the Denison TMA has reduced acid generation during the post rehabilitation period to less than 0.03 per cent and 0.15 per cent of the pre-water cover operating and during rehabilitation periods, respectively. In comparison to the revegetated Nordic TMA, the acid generation rates at the Denison and Panel TMAs have decreased to less than 1.6 per cent of that at the Nordic TMA. The acid generation rate at the Quirke TMA was comparable or only slightly lower than that at the Nordic TMA because of its interconnected, unique terraced cell configuration, having water levels at different elevations. Resident, historic acidity and oxidation reaction products, accumulated during operation and pre-water cover periods, are flushing from the upstream locations to the downstream cells, thus requiring a much higher equivalent limestone consumption for acid neutralisation at the Quirke TMA.

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