GEOCHEMICAL MANAGEMENT OF MINE WASTE AT DETOUR LAKE MINE

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ABSTRACT

Detour Lake Mine (DLM) is an open-pit gold mine in northern Ontario, Canada. Due to its relatively high tonnage (processing up to 32.85 million tonnes per year) and long operating period (of at least 20 more years), DLM is proactively managing mine waste materials and site water to reduce potential risks associated with metal leaching and acid rock drainage (MLARD). In 2022, DLM was the recipient of the International Network for Acid Prevention Leading Practice Award for implementation of best practices in the management of potentially reactive geologic materials. This document provides an overview of DLM's approach, including 1) the monitoring and management of waste rock and tailings based on their geochemical characteristics, 2) management of process water and mine contact water, and 3) a multidisciplinary progressive reclamation and research program that addresses several key aspects of effective mine closure, including reclamation cover optimization, ecosystem restoration with native species, and understanding of long-term geochemical behaviour for mine waste storage facilities. Collectively, these programs reduce potential geochemical, environmental, and financial risks, as well as support DLM's social license to operate.

Keywords: geochemical characterization, MLARD management, progressive reclamation

1.0 INTRODUCTION

Detour Lake Mine (DLM) is located in northeastern Ontario, Canada, approximately 300 kilometers northeast of Timmins. DLM is an active open-pit gold mine developed by expanding on the historical footprint of a former open-pit and underground mine. Commissioning of the ore processing facility was initiated in January 2013, and commercial production began in August 2013. DLM is owned and operated by Agnico Eagle Mines Limited.

Due to its relatively long life-of-mine and the large amount of material to be mined, it is imperative that mine waste (i.e., waste rock and tailings) be proactively managed to reduce potential geochemical, environmental, financial, and social license risks during operations and post-closure. This is accomplished through a suite of programs designed to manage waste rock, tailings, and site water, as well as progressive reclamation and closure planning.

Efforts to establish DLM's programs (including a multidisciplinary research campaign) began in 2010, prior to mine development, with strong support from corporate management. In 2022, DLM's geochemical management practices were recognized through a Leading Practice Award presented by the International Network for Acid Prevention (INAP). This document provides a brief overview of management programs, research initiatives, and recent results that contribute to practices at DLM.

2.0 WASTE ROCK & TAILINGS MANAGEMENT

Due to historical mining in the region, the geological materials (ore, waste rock, tailings, and overburden) at DLM have undergone multiple metal leaching and acid rock drainage (MLARD) assessments by various investigators (Robertson et al. 2012). Sampling, analysis and interpretation followed best-practice, industry-standard methods, such as those described in the Global Acid Rock Drainage (GARD) Guide (INAP, 2014). In general, it was predicted that MLARD potential at DLM low due to the relative lack of enrichment in sulfide and other metals. Nonetheless, MLARD potential was duly considered during both federal and provincial environmental permitting processes, and DLM initiated in the conservative management practices described below.

To provide greater assurance in the event of ARD during operations and/or closure, potentially acid-generating (PAG) and NAG waste rock materials are segregated into separate stockpiles (shown in Figure 1). PAG rock is stored in Mine Rock Stockpile 1 (MRS1) and the future Mine Rock Stockpile 3 (MRS3), with frequent co-disposal with NAG rock. Remaining NAG waste rock is used for construction or stored in Mine Rock Stockpile 2 (MRS2). Mine-contact water from all mine facilities, including stockpiles and Tailings Management Area (TMA) cells, is captured by the Water Management System, a network of collection ditches, ponds, pipelines and pumping infrastructure to ensure environmental protection. This system will be expanded to encompass new facilities that are constructed as the mine continues to develop. Discharge of surplus mine contact water occurs only at select, specially permitted locations, provided that water quality meets federal, provincial, and site-specific permitted criteria. Further details on water management at DLM is provided in Section 5.

DLM developed site-specific ARD classification criteria to optimize segregation and improve waste rock management during operations and closure. Classification criteria were developed based on long-term kinetic testing. Humidity cell data for DLM waste rock demonstrated that the ratio of acid generation and neutralization (i.e., relative release of sulfide and carbonate dissolution products) approaches 1, meaning that a neutralization potential ratio (NPR) of 1 would be a scientifically defensible threshold for the classification of NAG and PAG waste rock. To be conservative, the criterion for classifying PAG waste rock was defined as NPR≤1.5. Further classification based on estimated residual sulfur content following carbonate depletion is being considered.

DLM material testing, handling, segregation and storage are governed by the Waste Rock Management Plan (WRMP). Ore and waste rock classification is based on routine geochemical analyses of reverse circulation (RC) drilling samples (grade control samples), and blasthole drilling samples. Following analysis, DLM Geologists perform geostatistical analyses, interpolation and block modelling of carbon and sulfur distribution. After PAG areas within a blast are designed, the information is forwarded to the survey department with the rest of the ore polygons to mark out the limits in the pit with a high precision Global Positioning System (GPS). Blocks are identifiable using visual markers and in the electronic tracking system present in all mining equipment (Wenco). DLM Geologists, Dispatch Controllers, and Supervisors all work together to ensure that material is extracted appropriately and allocated to the correct location.

Monitoring results continue to support that there are low levels of sulfur in the deposit, and that there is an excess of neutralization minerals available in the waste rock to reduce the risk of ARD generation. Overall, 18% of waste rock has been classified as PAG over life-of-mine, similar to the EA prediction of 17%. Summary statistics for waste rock sulfur content, carbon content, and Neutralization Potential Ratios are presented in Table 1. Tracking of material movement over life-of-mine indicated that waste rock segregation is effective at DLM. 99.7% of PAG waste rock has successfully been allocated to MRS1, the designated PAG stockpile. PAG represents 0.07% of MRS2's total tonnage, due to materials erroneously deposited as single haul truck loads that could not be identified and rehandled. This amount of misallocated PAG rock is not considered to be of risk for acid rock drainage generation as it is encapsulated by an excess of NAG material.

Production tailings are governed by the same classification criteria as waste rock and are subject to frequent confirmatory sampling. Composites are collected weekly and undergo MLARD characterization monthly at a minimum. During baseline geochemical characterization, it was predicted that the tailings would be non-potentially acid generating with low metal leaching potential. Results from the tailings monitoring program since 2013 have been consistent with predictions until recent years, during which materials classified as PAG or uncertain with respect to ARD potential have been detected. DLM is investigating potential mitigation measures to reduce risks of tailings MLARD, if required.

Table 1. Summary statistics for analytical results from in-pit waste rock sampling (2012-2021)

	Waste and Ore Samples			Waste Samples Only		
	C %	**S %**	**NPR***	**C %**	**S %**	**NPR***
Count	90,897	90,897	90,768	65,801	65,801	65,713
Min	0.005	0.005	0.003	0.005	0.005	0.008
Max	3.4	5.0	828	3.4	5.0	828
Average	0.52	0.55	2.6	0.47	0.44	2.9
P25	0.25	0.2	1.7	0.23	0.17	1.8
Median	0.40	0.39	3.0	0.36	0.31	3.2
P75	0.68	0.75	5.0	0.59	0.58	5.3

NP*: Neutralization Potential=C% * 1,000/12

AP*: Acid Potential=S% * 31.25

NPR*: Neutralization Potential Ratio=NP*/AP*

3.0 WATER MANAGEMENT

In addition to its waste rock management, tailings management, and research programs, DLM has a several programs designed to be protective of environmental water quality. The DLM monitoring network includes 71 surface water stations and 141 groundwater stations. Regular data collection, analysis, and interpretation on a monthly and quarterly basis allow for risk identification and adaptive management. Risk evaluation, operational management and mitigation planning are also informed by:

1. The DLM Water Balance/Water Quality Model (WQWBM) captures water quantity and quality for both the operating and post-closure periods. The model considers sources from the TMA, open pit, and mine rock stockpiles, and predicts that water quality objectives that protect aquatic life. Water balance modelling was initiated at the onset of operations and refined over time, including through calibration with real monitoring data.
2. The WQWBM was used as the foundation for the DLM Integrated Surface Water-Groundwater Model, which captures hydrological and hydrogeological information to characterize and predict flows (e.g., pit draw down, water level fluctuations in the local watershed). This represents a fundamental tool for mine planning, permit compliance, closure planning, and addressing complex questions raised by internal, government, and Indigenous stakeholders.

Environmental protection is ensured through DLM's water management network, which collects seepage and runoff from all mine waste facilities through a system of ditching, pumping, and pipeline infrastructure. The modular design allows for the addition of treatment facilities if required. In 2020, a Mine Water Pond with a capacity of 3.5 Mm^3 was commissioned to provide additional contingencies for storage and treatment, if needed. As previously mentioned, discharge of surplus mine contact water (e.g., seepage and runoff from water rock storage facilities) occurs only at select, specially permitted locations, provided that water quality meets federal, provincial, and site-specific permitted criteria. Process water (i.e., water that has been used for gold extraction) is not planned for environmental discharge, and is instead stored separately in the Tailings Management Area and/or recycled through the Process Plant.

At closure, all mine contact water will be routed to the Main Pit, which will serve as a storage and pit lake treatment facility (Figure 2). Water collected from MRS1, the PAG storage facility, will be piped to the bottom of the pit lake, while other mine contact water will be deposited at the top of the pit lake. Due to the difference in salinity, the pit lake water column will stratify, isolating PAG contact water from non-PAG contact water. Metal concentrations in the pit lake water column's top layer will be further reduced through aging and semi-passive treatment via fertilization. Based on water balance modelling, it is expected that it will take approximately 100 years for the pit lake to fill. This long period will allow for monitoring, testing the proposed treatment, and adjusting management strategies if required. Pit lake concepts have been verified through studies of the former Placer Dome pit lake (prior to being drained for the resumption of mining activities by DLM) (Mueller et al. 2012) and numerical pit lake modelling for water balance and water quality. Financial assurance for approximately 200 years of post-closure maintenance and monitoring is included as a component of the DLM Closure Plan.

4.0 PROGRESSIVE RECLAMATION PROGRAM

Through the close collaboration of DLM's Mining, Technical Services, and Environment departments, waste rock storage facilities are designed and operated with closure in mind. Progressive reclamation throughout life-of-mine, through the application of relatively low-permeability soil covers and revegetation, will help mitigate MLARD by limiting the ingress of oxygen and water. Mechanisms for limiting oxygen and water ingress include runoff, absorption in the soil/root zone, and evapotranspiration by plants. Soil cover materials consist of glaciofluvial/glaciolacustrine till and organic peat that has been stripped from the open pit footprint and stored for future use in reclamation. The till material has relatively high neutralization potential and low potential for metal leaching.

The life-of-mine plan includes sequenced MRS designs for each year, with areas available for progressive reclamation identified, allowing for efficiency and long-term planning. The designs also include installing drainage features (such as vegetated swales and descending ditches) to promote water shedding from the MRS, reducing infiltration. As an example, the conceptual design for MRS1 is shown in Figure 3. The design and optimization of cover systems and revegetation strategies is informed by a long-term Reclamation Test Cover Program, described below.

Reclamation Test Cover Program

Cover system designs for mineral waste stockpiles are subject to multiple geotechnical considerations. It is critical to understand potential mechanisms for failure, including slope instability and excessive erosion, which are most common where slopes are steep and high levels of cover saturation are possible. The physical and hydraulic properties of cover materials are also crucial for design and performance. The effective establishment of vegetation is key to stabilization, promoting evapotranspiration, and achieving closure objectives. Empirical experimentation and observed performance of long-term field trials are therefore essential to cover system designs.

To address the above geotechnical considerations, DLM has designed and constructed approximately 10 hectares of vegetated Test Cover cells on the potentially acid generating mine rock stockpile (MRS1). The goal of the Test Cover Program is to evaluate the performance of different cover system options to support waste rock reclamation and landform design at DLM. The Test Cover program design includes 13 cover trial plots to evaluate geotechnical aspects (i.e., stability, erodibility, and constructability), vegetation (i.e., plant and root development, habitat development), and hydrogeological and hydrotechnical aspects (i.e., partitioning water between evapotranspiration, overland flow/runoff, and net percolation). To evaluate these aspects, the plots were designed with varying slope angles, soil thickness, composition and placement prescriptions, and vegetation prescriptions.

Comprehensive monitoring of the Test Cover Program is critical to ensure valuable information is gathered to inform the progressive reclamation activities in the subsequent years. Continual visual monitoring is conducted throughout the year using stationary camera poles strategically placed around the Test Cover Program area. Vegetation surveys are being conducted annually, to assess the performance of the vegetation prescriptions within each plot given the associated slope and cover thicknesses. Cover density and infiltration testing are being conducted to determine changes in soil cover density and hydraulic conductivity as a result of freeze-thaw cycling and vegetation growth. A central weather station in the Test Cover area monitors precipitation, solar radiation, wind speed and direction as well as evapotranspiration. The Test Cover Program will continue to provide valuable data for multiple years, and will help to further refine and increase the robustness of the best practices used in the DLM Progressive Reclamation Program. Detailed monitoring results to date are presented in a companion International Conference on Acid Rock Drainage (ICARD) 2022 paper (Raizman et al., 2022), and a summary is presented below.

The results from the 2021 monitoring have shown that there have been no large-scale geotechnical failures, and vegetation is becoming established in many places on the Test Cover. Compared to the previous year, apparent rates of erosion and deposition have slowed, and many erosional and some depositional features now have vegetation growing within or on them. These observations are interpreted to indicate a degree of stabilization of the reclamation covers. The main factors that are showing to contribute to the highest planted seedling survival are site preparation (using ripping techniques) and its effect on cover density, as well as peat content. Fine-fraction densities in sloped cover treatments that included excavator ripping are substantially lower than those that did not, and are associated with less potential restriction on root development in comparison to published ranges. These treatments are showing evidence of increases in seedling survival of approximately 25-40% (i.e., survival rates in ripped treatments of 60-70% compared to rates of 30-40% in non-ripped treatments). Despite high initial mortality, the densities of planted conifers established on the MRS1 test-cover trial are consistent with the goal of producing closed-canopy conifer forests that contribute to habitat goals for caribou, as conifer densities in the range of 1,000-1,200 stems per hectare can develop into fully stocked stands. The additional plants and diversity provided by the mixed planting with deciduous species (including alder) contributes to biodiversity and more rapid achievement of reclamation goals (i.e., establishment of plant cover to reduce erosion, production of organic litter to support nutrient cycling, biodiversity).

In 2021, there was substantial natural regeneration by species that were not manually planted or seeded in the initial trial setup, contributing to 80-90% of the total plant cover across the Test Cover area. The major species/ species groups that were naturally regenerating were native mosses, and exotic sweet clover and redtop. Currently, exotic species present in the Test Cover area are providing beneficial cover and nutrients for the native species, and they will continue to be monitored overtime to ensure competition problems with other desired native species are not occurring.

Progressive Reclamation Execution

In addition to the ten-hectare Test Cover area described above, and ten hectares of reclamation on MRS1 in 2020, approximately ten hectares were reclaimed on MRS1 as part of the Progressive Reclamation Program in 2021. Site preparation and soil placement was completed on an additional 10 hectares on MRS1 in 2021, and this area will be revegetated in 2022. Data from the years of research conducted at DLM are contributing to the initial successes of this project, including:

- A minimum cover thickness and placement strategies determined using the available results from the Waste Rock Research Program;
- A target slope grade to maximize cover stability and vegetation success while minimizing the overall stockpile footprint, as determined through results of the Test Cover Program;
- A native species vegetation prescription with a selection of species that have demonstrated establishment success and sustained growth in the University of Guelph Research Program and the Test Cover Program;
- The incorporation of the most successful soil amendments (peat and fertilizer) as shown in the results of the Vegetation, Soil Health and Amendment Trial and in the preliminary results of the Tailings Revegetation Trial; and
- The procurement of a fertilizer/seed spreading drone, after difficulties were encountered using manual hand broadcasting methods for the Test Cover Program. The drone allows for the design of flight paths of set distances and flight speeds, resulting in more even coverage of native seed and fertilizer at more accurate spreading rates.

As a result, the 2021 progressive reclamation area was successfully covered, amended, planted with approximately 40,000 trees, and seeded with a native grass species mix. Data collection in 2021 will help to confirm the successful establishment of the vegetation and inform the Progressive Reclamation Program in subsequent years.

5.0 SUPPORTING RESEARCH PROGRAMS

DLM routinely undergoes technical studies to support operations and closure (e.g. WBWQM, Pit Lake Model, Cover System Modelling, pre-feasibility level designs for post-closure water management, End Land Use Plan, stockpile design optimization, which includes sequencing of progressive reclamation and water management features). DLM also hosts multiple interdisciplinary research and development programs that directly inform site management, including those described below.

Waste Rock Research Program

In 2011, DLM initiated research partnerships with the University of Waterloo, the University of Alberta and Carleton University, to characterize the historic and current waste rock storage facilities' physical and geochemical properties. Research and monitoring for this program will continue throughout life-of-mine to create an overall record of 50 years. Findings from this program will continuously be used to improve the DLM Progressive Reclamation Program, and results from the Waste Rock Research Program have already been incorporated into research on soil cover variables for reclaiming mineral waste stockpiles. Additionally, this program will generate a solid basis for the expected behaviour of waste rock material post-closure, providing a critical design basis for reclamation planning and closure costing. The following research questions are being addressed through the ongoing research program:

1. How do hydrology, thermal, gas transport and biogeochemical regimes evolve following deposition of waste rock and mineralized rock?
2. What are the scaling relationships between small-scale laboratory measurements and measurements made on the operational waste-rock stockpiles at the Detour Lake site?
3. What is the influence of a soil cover on the hydrological, thermal, gas transport and biogeochemical regimes within weathered sulfide-bearing waste-rock stockpiles?
4. What is the influence of progressive reclamation, consisting of different waste-rock slope, with different soil-cover thickness, topography and vegetation on the porewater chemistry, hydrological, thermal, gas transport and biogeochemical regimes within freshly deposited waste rock?

Measurements made during the 2021 field season on the MRS1 Test Cover Trial found that circumneutral pH continues to be observed at all sample locations in the MRS1 waste rock boreholes and cover test pits. Results of porewater chemistry samples do not currently indicate a significant difference in water chemistry among different rock slope and soil cover configurations on the MRS1 Test Cover, however the area is still developing. The ubiquitous presence of carbonate alkalinity, elevated calcium and magnesium concentrations and concurrently, stable potassium, silicon and aluminum concentrations in the porewater, suggests that carbonate mineral dissolution is currently the dominant acid neutralization mechanism consuming acidity released by sulfide mineral oxidation. Partly oxidized sulfur and iron species detected in the porewater indicate that pyrrhotite oxidation is occurring. This observation will help improve future sulfide oxidation models for waste rock stockpiles. The physical and hydrological findings of the project, together with the conceptual model, form a basis for more comprehensive and complex surface flux boundary modelling to understand infiltration into new stockpiles and flux of water and potential constituents to the subsurface.

Tailings Revegetation Trial

An additional component of the Progressive Reclamation Program is the Tailings Revegetation Trial. The goal of the Tailings Revegetation Trial is to assess various methods for reclamation of final tailings surfaces. Developing practical knowledge and techniques in this area is critical, particularly as the majority of tailings cells will be reclaimed during life-of-mine.

In 2019, mesocosms were established to test the performance of various soil amendments applied to beached tailings. Fertilizer, mine till, peat, combinations of the three, as well as a combination of mine till and biosolids were applied to mesocosms filled with beached tailings. Each mesocosm was then seeded with a native seed mix and planted with native coniferous and deciduous species. Key information that will be gathered from this trial include the evaluation of cover and amendment combinations for vegetation establishment and long-term sustainability, plant metal uptake, and seepage water quality change over time from the experiment mesocosms.

In 2021, a one-hectare trial was established on the TMA Cell 1 in order to scale up from the mesocosm trial. A layer of peat (approximately 30 cm thick) was applied directly to the beached tailings within Cell 1 in the winter of 2021. Fertilizer and a native seed mix were hand broadcast, and native woody species were planted in the fall of 2021. Data will be collected in 2022 related to vegetation health and establishment as well as soil quality.

The data collected from this research will help to develop results-driven tailings reclamation practices for long-term vegetation establish. This is critical due to the general difficulty of successful, sustained reclamation of mine tailings surfaces.

Restoration Research with University of Guelph

A collaborative research program was established by University of Guelph and DLM in 2013, and is intended to continue throughout the life of the mine. The long-term objective is to evaluate the most effective methods for establishing habitats and native plant communities during progressive reclamation and closure. Current research studies include 1) vegetation and soil trials, 2) establishment of lichen and biological soil crusts, and 3) forest road restoration. In addition, a long-term, 10-hectare reclamation test cover area was established in 2019. The studies are progressing and yielding encouraging results for refining strategies for vegetation establishment, growth, and enhancement in the context of reclamation planning at DLM.

6.0 CONCLUSIONS

DLM is a relatively high tonnage gold mining operation with a long life-of-mine. To reduce potential geochemical, environmental, financial and social license risks, DLM employs a broad range of programs to ensure best practices are implemented for the management of mine waste, mine contact water, and reclamation. Many of the programs were designed or initiated prior to mine development, and have continued to be refined throughout the operating period.

Holistically, DLM's programs contribute to environmental protection during the operating period and post-closure through the mitigation of risks associated metal leaching and acid rock drainage, as well as eventual ecosystem restoration. Further, monitoring results and ongoing studies contribute to continuous improvement and guide the evolution of DLM's management and research practices.

7.0 ACKNOWLEDGEMENTS

We gratefully acknowledge current and previous leaders and collaborators who have supported DLM's programs over the past decade, including J. Robertson, P. Beaudoin, M.H. Turgeon, T. Desormeaux, M. Bingham, N. Francoeur-Leblond, M. Leclair, D.W. Blowes, G.W. Wilson, J. Bain, and R.H. Hanner. We thank the many university students and mine personnel who contributed to field work and laboratory analysis. Research funding was provided by Agnico Eagle Mines Limited and the National Science and Engineering Research Council (NSERC).

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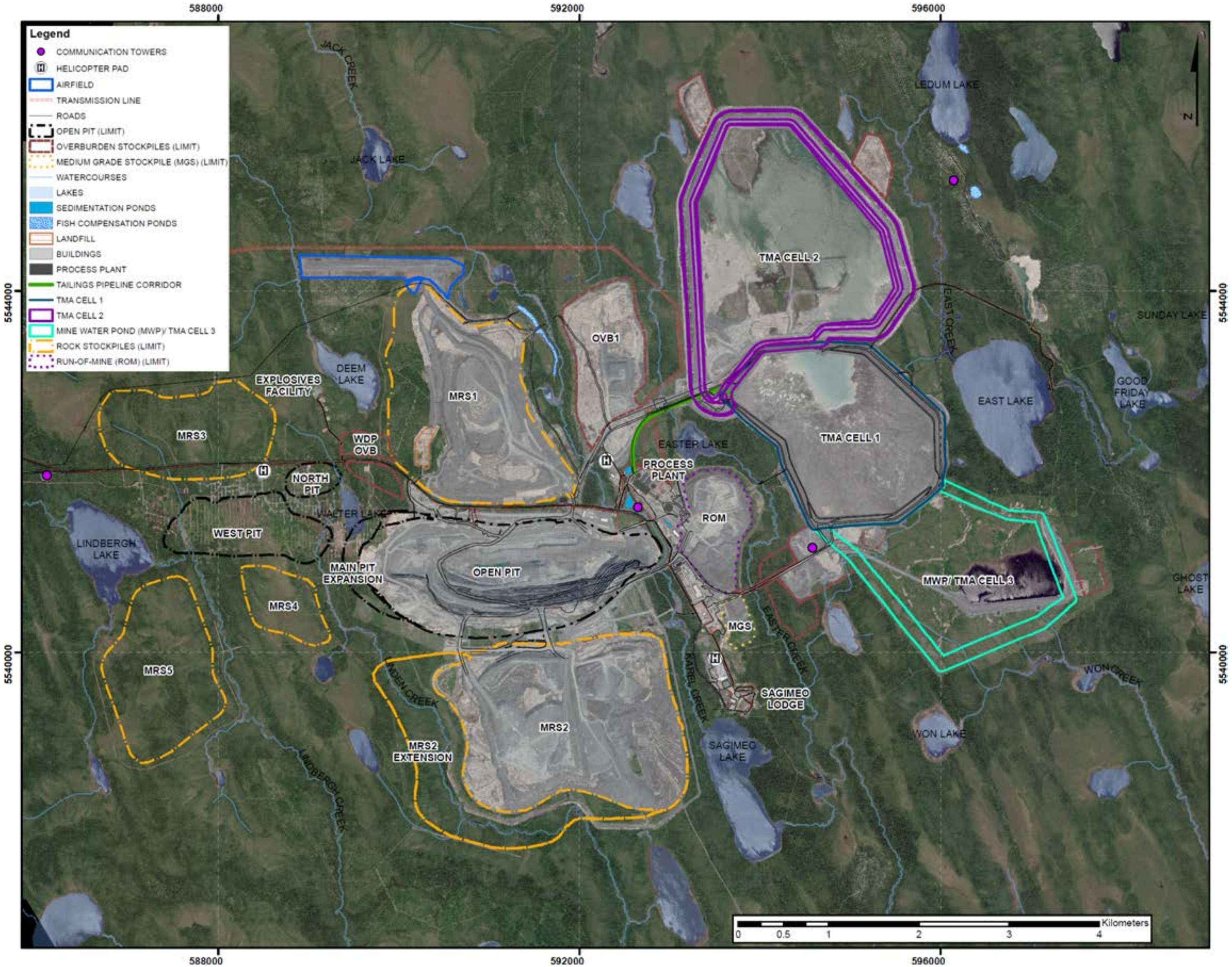
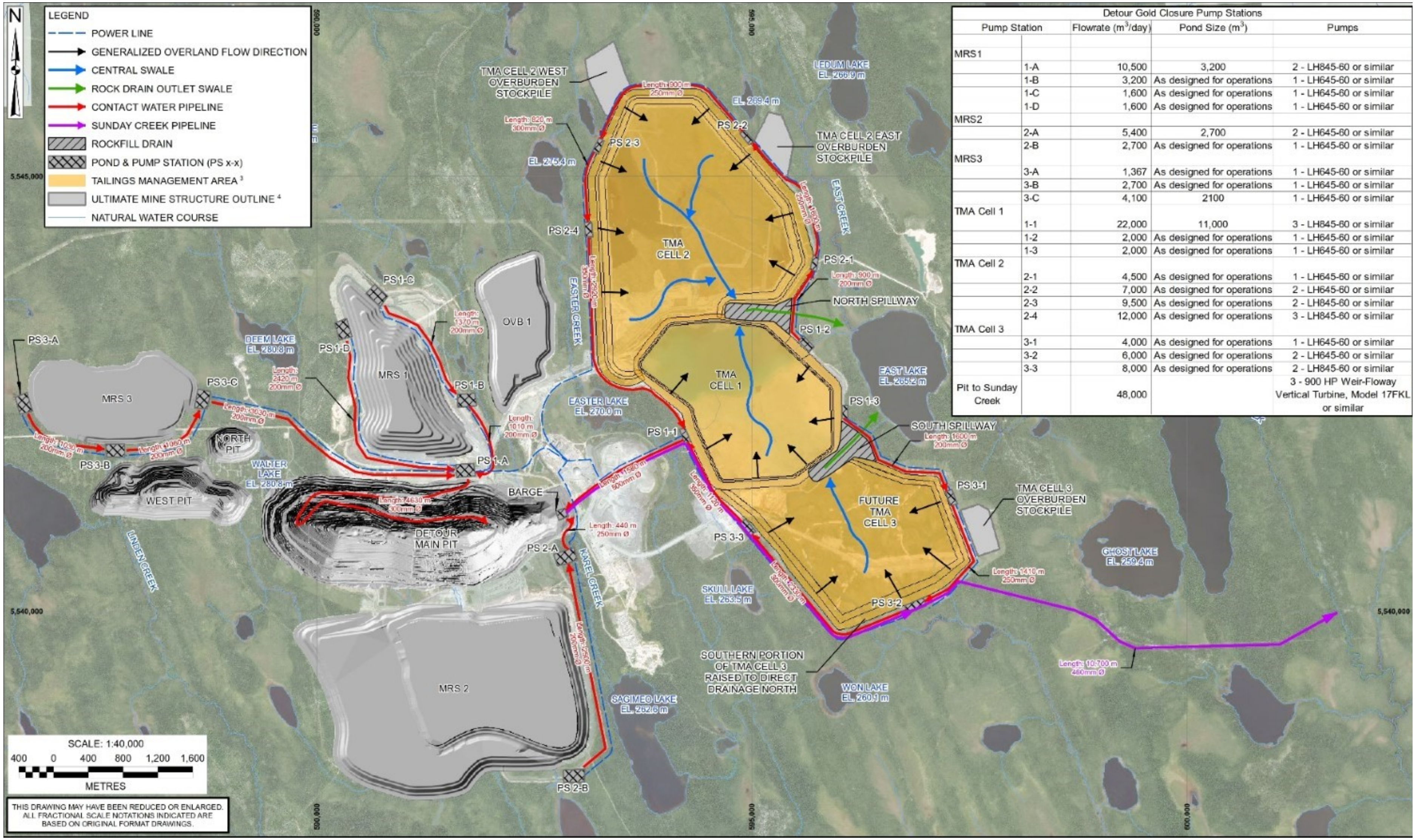


Fig. 1. Detour Lake Mine Site Layout



Detour Gold Closure Pump Stations

Pump Station		Flowrate (m^3/day)	Pond Size (m^3)	Pumps
MRS1				
	1-A	10,500	3,200	2 - LH845-60 or similar
	1-B	3,200	As designed for operations	1 - LH645-60 or similar
	1-C	1,600	As designed for operations	1 - LH645-60 or similar
	1-D	1,600	As designed for operations	1 - LH645-60 or similar
MRS2				
	2-A	5,400	2,700	2 - LH645-60 or similar
	2-B	2,700	As designed for operations	1 - LH645-60 or similar
MRS3				
	3-A	1,367	As designed for operations	1 - LH645-60 or similar
	3-B	2,700	As designed for operations	1 - LH645-60 or similar
	3-C	4,100	2100	1 - LH645-60 or similar
TMA Cell 1				
	1-1	22,000	11,000	3 - LH845-60 or similar
	1-2	2,000	As designed for operations	1 - LH645-60 or similar
	1-3	2,000	As designed for operations	1 - LH645-60 or similar
TMA Cell 2				
	2-1	4,500	As designed for operations	1 - LH645-60 or similar
	2-2	7,000	As designed for operations	2 - LH645-60 or similar
	2-3	9,500	As designed for operations	2 - LH845-60 or similar
	2-4	12,000	As designed for operations	3 - LH845-60 or similar
TMA Cell 3				
	3-1	4,000	As designed for operations	1 - LH645-60 or similar
	3-2	6,000	As designed for operations	2 - LH645-60 or similar
	3-3	8,000	As designed for operations	2 - LH845-60 or similar
Pit to Sunday Creek		48,000		3 - 900 HP Weir-Floway Vertical Turbine, Model 17FKL or similar

Fig. 2. Schematic of site layout and water management network at closure, including deep injection of PAG rock contact water

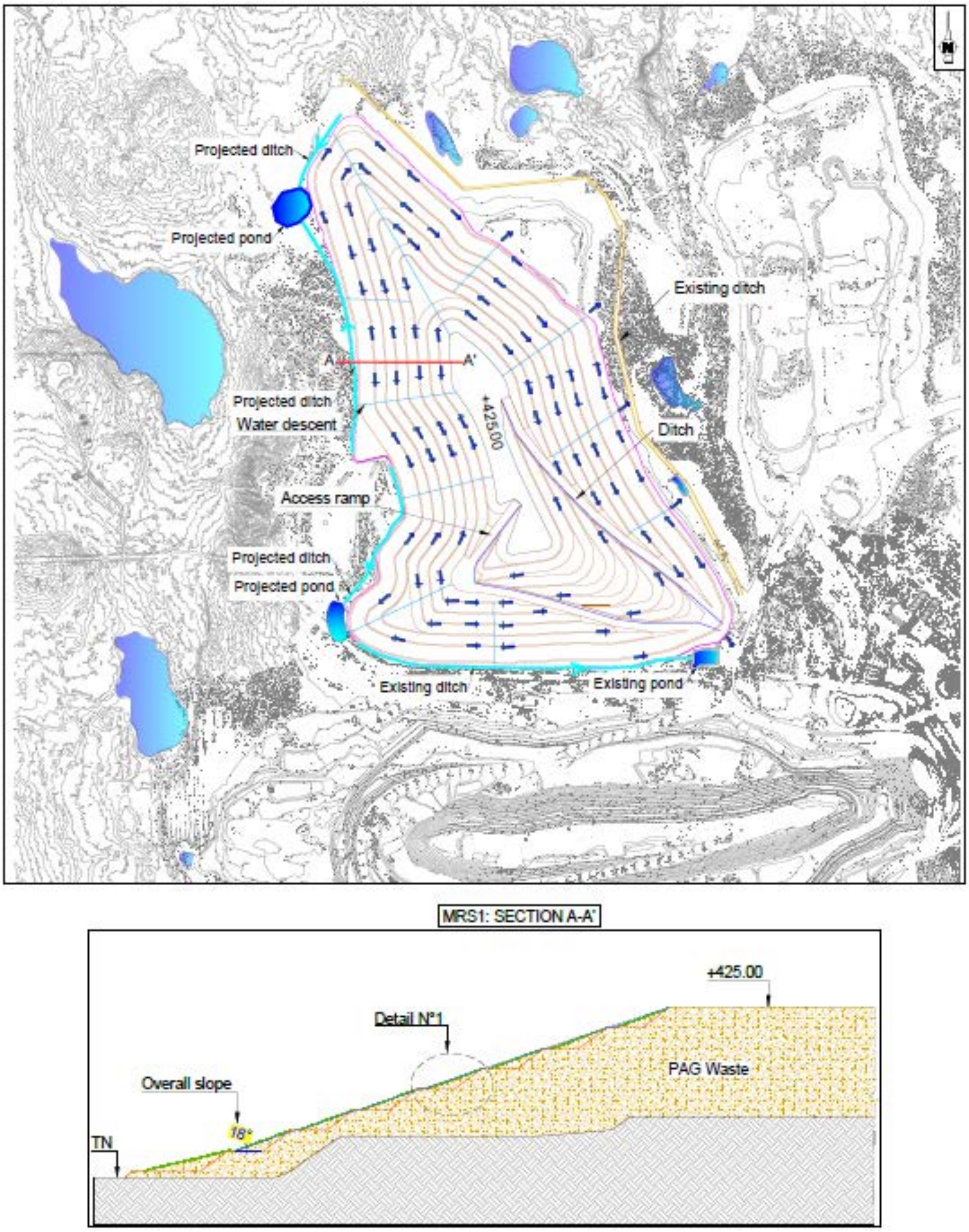


Fig. 3. Conceptual design for MRS1, including water management features. This storage facility is planned to undergo progressive reclamation throughout life-of-mine, ending in complete surface area coverage and revegetation at closure