MINE ROCK STOCKPILE RECLAMATION TRIAL, DETOUR LAKE MINE: DESIGN, CONSTRUCTION, AND LESSONS LEARNED

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ABSTRACT

Designs for reclamation cover systems on waste rock stockpiles must consider the specific objectives of the cover systems and the unique features of individual mine sites. Configurations and characteristics of waste material, characteristics and availability of reclamation material, suitability of vegetation, and climate are some of the considerations. These factors require geotechnical, hydrological, and ecological design decisions be made to achieve site-specific and overall closure objectives; however, in early stages of mine development the characteristics and configurations of the reclamation design which will lead to the better reclamation outcomes are unknown.

Guidance for beneficial strategies for landform design and progressive reclamation are being developed at Detour Lake Mine by designing, establishing, monitoring, and evaluating a large-scale (10 ha) Test Cover Trial on waste rock stockpiles during the early stages of mining. The design included 13 cover trial treatments with varying characteristics to consider geotechnical aspects (i.e., constructability, stability, erodibility), ecological aspects (i.e., plant and root development, habitat development), and hydrological aspects (i.e., partitioning water between evapotranspiration, surface runoff, net percolation). The available cover materials were silt rich with variable amounts of peat. To accommodate the unique and challenging properties of these materials, design variables for the Test Cover Trial included ranges in waste rock slope angles, in reclamation cover thickness, composition, and surface grading, and in revegetation treatments.

Design modifications were required during construction to accommodate operational challenges and site conditions. Modifications were necessary to decrease cover density, to account for minimal to variable peat content, and to compensate for reduced planting densities, while still maintaining the design intent. Insights into operational-scale construction methods and techniques gained throughout the construction process are being applied to ongoing progressive reclamation at the mine. Results of ongoing monitoring are described in a companion paper by Harrington et al.

Key Words: waste rock, cover design, revegetation, soil-moisture, density mitigation, northern Ontario

INTRODUCTION

The Detour Lake Mine (DLM) is a conventional open pit, hard rock gold mine owned by Agnico Eagle Mines Limited. The mine is located approximately 300 km northeast of Timmins and 185 km northeast of

Cochrane, Ontario, Canada. The site is located within the Abitibi Uplands, an eroded upland that constitutes a drainage divide between the Hudson Bay and St. Lawrence River watersheds. The local area is characterized by low, flat-lying, poorly exposed bedrock ridges predominantly covered by glacial sediments and large expanses of organic terrain. Topography at the Detour Lake Mine is subdued, ranging from approximately elevation 255 m to 315 m. Local ecosystems are a mosaic of open black spruce (*Picea mariana)* forests with sphagnum moss *(Sphagnum* spp.*)* on depressional, organic soils; wet, lowland, closed-canopy black spruce-larch *(Larix laricina)* forests on organic soils, and closed-canopy upland spruce *(Picea* spp.*)*-jack pine *(Pinus banksiana)* - feathermoss *(Pleurozium schreberi)* forests on mineral soils. DLM was developed on the historical footprint of an open pit and underground mine that operated from 1983 until closure in 1999. The current DLM operation was commissioned in 2013, with a projected mine life to 2040 or later.

Reclamation at DLM includes several overall objectives developed in consultation with partnered Indigenous communities. These objectives include restoration of pre-development ecosystems, creation of habitat for woodland caribou and other native species, and provision of a safe available area for traditional and economic use. Due to the projected long mine life, phased implementation of progressive reclamation activities will occur during mine operations. Progressive reclamation (i.e., reclamation concurrent with mining operations) is beneficial for adaptive management of the reclamation design and construction, and allows for assessment, design, testing, and refinement of techniques over multiple years to develop and refine reclamation prescriptions and successful implementation methods. As part of the progressive reclamation program and mine closure planning, a reclamation cover trial at Mine Rock Stockpile 1 (MRS1) was initiated as a component of a long-term multidisciplinary research program (Raizman et al., 2022). This paper discusses the design and construction of the MRS1 Test Cover Trial (Test Cover Trial) program that was designed and constructed to compare different options for progressive reclamation of the MRS, with consideration of hydrological, geotechnical, and ecological performance.

<u>End Land Use Plan</u>

Reclamation at DLM is in part guided by an End Land Use Plan (ELUP), which presents an overarching site-wide reclamation “blueprint” to support development of more detailed revegetation planning and other reclamation tasks. The DLM ELUP has been developed through collaboration between mine staff and Indigenous communities, and includes two primary goals:

- Re-establish pre-mine ecosystems to the extent possible given the biophysical constraints imposed by mining (e.g., changes to topography and surficial materials). The intent of this goal is to return a variety of habitat values and to create a landscape that will support traditional Indigenous land uses, including hunting, plant gathering, fishing, and trapping.
- Replace caribou habitat, focused on establishing closed-canopy conifer forests.

The ELUP provides information on pre-mining ecosystems and projected post-closure ecosystems. This information was used in the design of the Test Cover Trial to support development of reclamation-cover and revegetation prescriptions, by linking cover characteristics to plant species adapted to growth in similar conditions. Specifically, ELUP post-closure projections indicated the prevalence of spruce-jack-pine uplands on the covered MRS1 facility, and these projections were used to guide development of cover and revegetation prescriptions for the Test Cover Trial design.

DESIGN BASIS

Design Goals and Objectives

The Test Cover Trial was designed in 2018 to evaluate variables that may affect the success of progressive reclamation at DLM, and to provide data and knowledge in support of ongoing design for the ultimate closure of the MRS and other mining landforms. The goal of the Test Cover Trial program is to evaluate the performance of different cover system options to support waste rock reclamation and landform design at DLM. The Test Cover Trial design considered geotechnical, hydrogeological, hydrotechnical (i.e., water balance and design events), vegetation (i.e., plants and roots) aspects of the cover system, and aesthetic considerations. Geotechnical considerations included constructability, stability, and erodibility. The hydrogeological and hydrotechnical aspects of the design and instrumentation plan were developed to determine the dominant controls on the fate of water (e.g., partitioning between evapotranspiration, overland flow, net percolation, and surface runoff).

The objectives of the Test Cover Trial program included determining the steepest slope on which a cover system could be reliably maintained; evaluating the relative performance of different reclamation cover prescriptions; assessing the performance of vegetation with respect to establishment success, development trajectories, biodiversity, and erosion; and evaluating the partitioning of the water balance between evapotranspiration, surface runoff, and infiltration. The design included creation of plots within the footprint of the Test Cover Trial location to evaluate combinations of the different design components of the cover system. Thirteen plots were developed with varying cover systems that considered slope angle, aspect/exposure, cover thickness, composition and placement prescriptions, and revegetation prescriptions. The scale of the plots was such that they were large enough to be constructed with mine-scale equipment and to reduce edge effects between adjacent plots and the surrounding (unreclaimed) environment.

Site Selection and Design Criteria

A site selection process was implemented as part of the design, as the constraints of the chosen site influenced the design basis for the trial. Primary criteria considered as part of the site selection process included that the location would:

- have both sloped and flat areas,
- remain undisturbed for 15 to 30 years,
- be amenable to construction with mine-scale equipment,
- have a minimum of two slope aspects,
- be a minimum of one bench in height (i.e., 10 m), and
- be large enough to support a minimum of three slope angles.

Based on these site selection criteria, an area on the northeast corner of MRS1 was chosen (Figure 1). The selected area was approximately 10 hectares, included one bench of waste rock approximately 10 m high, and met the primary criteria. The site had two primary aspects (north and east) and, at the time of selection, had not been regraded after waste rock placement.

Figure 1. Test Cover Trial site location. MRS1 is approximately 2,300 m in length from north to south.

Slope Regrading and Cover Design

The available and proposed reclamation cover materials at DLM consist of fine grained and cohesionless materials of the Cochrane Drift and Cochrane Till surficial deposits. These deposits are primarily sandy silt to silt and sand with some to trace gravel. Other available materials such as organic soils (peat) and clay were available in smaller quantities but were typically intermixed in stockpiles with the Cochrane deposits. The silt-rich deposits are susceptible to erosion or failure on slopes: moving water can lead to rilling and gullying; slip-off failures may expose waste rock; and material deposited at the toes of slopes may block ditches or access roads. The appropriate slope angle, and other cover and vegetation characteristics, required to mitigate these potential failure mechanisms during design were unknown.

As a result, the Test Cover Trial design considered five different slope angles for regrading of the waste rock, including angle of repose (β=36°), 2.0H:1V (26°), 2.5H:1V (22°), 3.0H:1V (18°), and 4.0H:1V (14°). The range of slope angles was chosen to develop end members that could reliably maintain a cover system, with the potential that one or more slope angles may have a failure of the cover system (e.g., extensive erosion and/or slip-off failure of the cover). The plateau area on the top of the Test Cover Trial was effectively flat.

A single layer isolation cover, consisting of unsegregated overburden (i.e., peat, clay and Cochrane Drift/Till) was proposed for the Test Cover Trial design. The cover material was prescribed to consist of approximately one third peat, by volume, with the mineral component being an approximately even mix of Cochrane Drift/Till and clay, to develop a peat-mineral mix. The Test Cover Trial design considered four different cover thicknesses on the plots, including no cover, 0.3 m, 0.7 m, and 1.0 m. A 0.7 m cover thickness was designated as the base case thickness in the design process. This thickness was determined from model simulations that considered changes in rooting-zone water storage driven by climate, particle-size distributions of cover materials, and net radiation on a slope. The average growing-season climatic moisture deficit, described as potential evapotranspiration (PET) less precipitation (P), for MRS1 is approximately 60 mm to 70 mm, depending on data sources used and the assumed length of growing season. Thus, a cover with the capacity to store 60 mm to 70 mm of water over a range of plant-available tensions should be able to provide water to meet vegetation demands in an average growing season. To account for climatic variability and, in particular, drier-than-average growing seasons, the water-storage target for the cover was set at 80 mm. Therefore, this target required a design cover depth of approximately 0.7 m, which was used for the majority of the trial cover plots.

Other design characteristics included two types of surface grading, including corrugated topography with parallel rills (i.e., 0.1 m to 0.25 m of relief) oriented downslope to encourage water removal from the sloped areas, and microtopography to create local topographic highs and lows (i.e., 0.05 m to 0.15 m of relief) to break up surface runoff flows and create small microclimates for vegetation. A summary of the cover design characteristics for the 13 trial plots is provided in Table 1.

Revegetation Design

The overall closure objectives for DLM include reclamation of pre-development ecosystems and development of habitat to support woodland caribou and other native species. In addition, the design objectives for the Test Cover Trial included reducing erosion through rapid establishment of vegetation and reducing net percolation through increased evapotranspiration. These objectives were used to develop revegetation prescriptions for the Test Cover Trial; however, the objectives are potentially conflicting. For example, primary species required for woodland caribou habitat (i.e., closed canopy mature conifer forest) do not have rapid establishment for erosion control in comparison to grasses. In addition, deciduous forest would increase evapotranspiration; however, at early seral stages, deciduous species are preferred by moose for browsing, which may conflict with objectives of establishing caribou habitat. The design approach adopted for the Test Cover Trial sought to balance these objectives through some initial rapid establishment of non-propagating grasses that will be replaced by native plants through ecological succession.

As a result of these trade offs and uncertainties, four revegetation prescriptions were included in the Test Cover Trial:

- Hydraulic seeding (hydroseeding) of native grasses and a fall rye *(Secale cereale)* nurse crop in combination with fertilizer, mulch, and tackifier on steeper slopes.
- Broadcast seeding of native grasses in combination with fertilizer. Broadcast-seeded areas also included an agronomic nurse crops (i.e., fall rye or oats [*Avena sativa*]).
- Conifer planting of container seedlings of white spruce (*Picea glauca*) and jack pine, to establish closed-canopy conifer forest for caribou habitat.

Deciduous trees and shrubs inter-planted with conifer seedlings to provide additional leaf area for transpiration/water removal, to facilitate conifer establishment, and to provide diversity of established vegetation.

Table 1. Test Cover Trial cover plot treatment summary.

Plot number	Slope Angle						Slope Aspect			Cover Thickness					Surface Grading		Vegetation Type					
	Angle of Repose (β=36°)	2.0H:1V (β=26°)	2.5H:1V (β=22°)	3.0H:1V (β=18°)	4.0H:1V (β=14°)	Flat	North	East	Northeast	0.0 m	0.0 m (slope), 0.3 m (bench)	0.3 m	0.7 m	1.0 m	Corrugated	Microtopography	Hydraulic Seeding	Broadcast (Native Seed Mix, Winter Kill)	Conifer, Interseeding (Native Seed Mix, Winter Kill)	Conifer and Deciduous, Interseeding (Native Seed Mix, Winter Kill)	Conifer, Delayed Interseeding	Conifer and Deciduous, Delayed Interseeding
01	●						●			●							●					
02		●						●			●				●		●					
03		●						●					●		●			●				
04			●				●				●							●				
05			●				●					●				●					●	●
06			●					●					●			●					●	●
07			●				●						●		●				●	●		
08			●					●						●		●			●	●		
09				●			●						●			●					●	●
10A				●			●						●			●			●	●	●	●
10B				●				●					●		●				●	●	●	●
11					●				●				●			●					●	●
12					●				●				●		●				●	●		
13						●							●			●						●

The revegetation prescriptions were also designed to test the effects of immediate versus delayed interseeding of native grasses within planted areas. Some previous reclamation research (Straker, O'Brien, & Jones, 2010; Straker, O'Brien, Jones, & Berdusco, 2002) has shown that excessive competition between grasses and planted trees/shrubs can result in high mortality of the planted stems; however, co-establishment of grasses may help to provide some protection from wind desiccation and surface erosion. The vegetation prescription assigned to each trial plot is summarized in Table 1.

Instrumentation Design

The instrumentation program for the Test Cover Trial was designed to evaluate the near surface water flow and water budget in the reclamation cover. Understanding the water budget in the cover was important to meet the objective of evaluating the partitioning of the water balance between evapotranspiration, surface runoff, and infiltration, and quantifying water flow quantity and quality from the MRS. In addition, the instrumentation design was intended to allow examination of changes to the cover through vegetation development, seasonal effects (e.g., freeze-thaw processes), and weather events.

The instrumentation design included test pits on the slope with sensors at multiple depths in the reclamation cover to measure volumetric water content, soil-water potential, and soil temperature. A meteorological station was designed for the plateau (Plot 13). Finally, standpipe piezometers were designed to provide data on groundwater elevation below the trial and to allow groundwater sampling.

CONSTRUCTION METHODS

Construction of the Test Cover Trial occurred between October 2018 and September 2019. Slope regrading was completed in October and November 2018, and construction was stopped over the winter. Reclamation material cover placement was started in May 2019, and additional activities such as road and ditch construction, instrumentation installation, seeding, and planting were completed intermittently between June 2019 and September 2019.

Slope Regrading and Reclamation Material Placement

Reclamation cover placement was completed by loaded articulated haul trucks which transported the reclamation material to the plots. After hauling and dumping, the reclamation material was typically spread using a dozer (Figure 2). The cover construction at the Test Cover Trial site was the first large-scale reclamation material placement at DLM. As a result, modifications to the design and specifications, and field fitting of the design were required to meet operational challenges and site conditions, while still maintaining the design intent.

Figure 2. Cover placement during construction of the Test Cover Trial; view looking approximately south.

The initial specifications indicated the reclamation cover material was to include up to 30% peat, by volume, which was the assumption used in the modelling supporting the initial cover design. The material available during the construction of the Test Cover Trial had less than 10% peat, by volume. However, this same material composition was determined to be representative of that which would be available for future progressive reclamation. Availability of peat during construction occurred intermittently and, where practicable, peat was added to create a peat-mineral mix on selected plots (Plot 05, Plot 06, and portions of Plots 10B and 13).

Additional challenges were encountered during material placement, as spreading with dozers to the specified cover thickness resulted in highly compacted reclamation material. The target maximum dry density for the reclamation cover was 1600 kg/m^3. This design density was chosen so that root propagation and subsequent vegetation establishment and growth would not be limited. However, compaction testing during construction indicated that the constructed dry density of the reclamation material averaged 1950 kg/m^3, in part due to the limited peat content, but also due to trafficking by equipment. A range of methods to loosen the cover were investigated, and a ripping tooth on an excavator was determined to be best available tool. The ripping tooth was used on selected areas of the Test Cover Trial to loosen the surficial cover (to approximately the full cover thickness) in two different ways: ripping parallel to the slope to create loose corrugated topography; and cross-ripping to create loose microtopography. Cover material on Plot 13 was paddock dumped by haul trucks in rows and an excavator was used to spread and cast the reclamation material to create paddock dumped microtopography. The as-constructed conditions of the reclamation cover material are shown in Figure 3.

Revegetation Activities

Revegetation of the Test Cover Trial was conducted intermittently between August 1, 2019, and September 15, 2019, and consisted of three primary activities, hydroseeding, broadcast seeding, and planting. Hydroseeding was completed on two plots with the steepest slope angles, angle of repose and 2H:1V (26°), as exposed waste rock (Plot 01) was not amenable to broadcast seeding or planting, and to test hydroseeding on a thin cover (Plot 02). Hydroseed was applied at a rate of 40 kg/ha of fall rye and 30 kg/ha of the custom native-seed mix (Table 2). All plots, other than the hydroseeded plots, received broadcast seeding. Plot 03, the slope transition between Plot 03 and Plot 06, and the sloped portion of Plot 04 received broadcast seeding only, with application of 40 kg/ha fall rye and 30 kg/ha of the custom native seed mix. No planting occurred on these plots.

Table 2. Custom native seed mix used in hydroseeding and broadcast seeding.

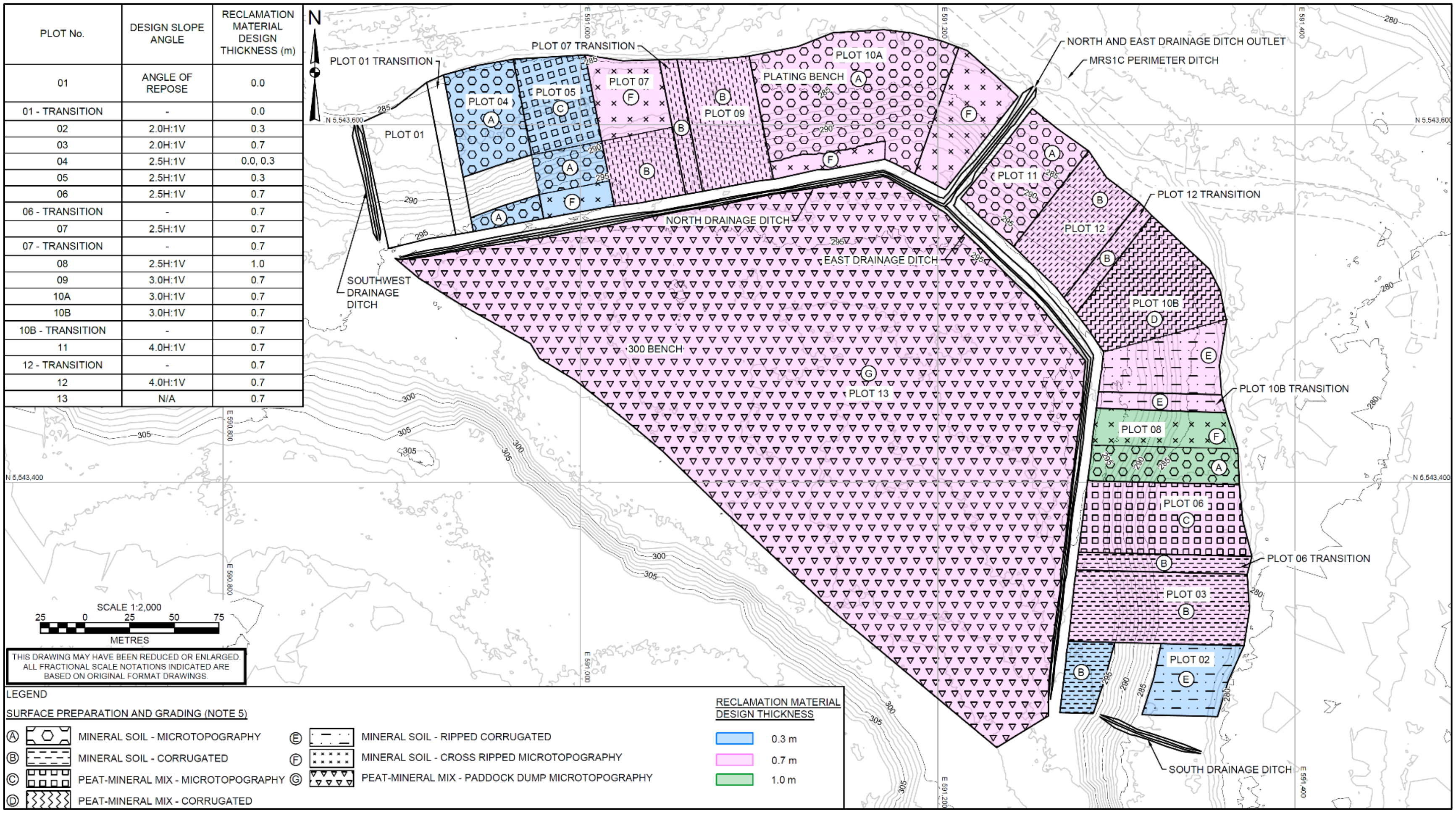
Species	Percentage by Weight (%)
Alpine bluegrass (*Poa alpina*)	8
Fringed bromegrass (*Bromus ciliatus*)	43
Ticklegrass (*Agrostis scabra*)	2
Streambank wheatgrass (*Elymus lanceolatus*)	23
Slender wheatgrass (*Elymus trachycaulus*)	24

A total of 26,644 plants were installed on the Test Cover Trial area, including the installation of conifers (white spruce and jack pine) in all planted plots at a target density of 2500 stems per hectare (sph). Selected plots were to be inter-planted with deciduous tree and shrub species with equal proportions of balsam poplar, trembling aspen, green alder, and willows (multiple species). However, due to issues with seedling propagation, an insufficient supply of these species resulted in only green alder being used for the deciduous inter-planting at a density of approximately 1400 sph.

Additional species were planted at low numbers to test the ability of these species to establish on sloped covers. These species included: northern bush-honeysuckle (*Diervilla lonicera*), tamarack (*Larix laricina*), balsam poplar (*Populus balsamifera*), trembling aspen (*Populus tremuloides*), pin cherry (*Prunus pensylvanica*), prickly rose (*Rosa acicularis*), raspberry (*Rubus idaeus*), plane-leaved willow (*Salix planifolia*), pussy willow (*S. discolor*), and prairie willow (*S. humilis*). Due to low numbers, these species were primarily planted in rows in the slope transition areas between Plot 07, 10B, and 12. Monitoring of vegetation establishment is conducted through 84 circular, fixed-area permanent sample plots. The as-constructed conditions of the revegetation program and location of the permanent sample plots are shown in Figure 4.

Instrumentation Installation

Volumetric water content, soil-water potential, and soil temperature sensors were installed in 31 test pits excavated in the reclamation cover at depths of 0.2 m, 0.5 m, and 0.7 m or 0.8 m depending on cover thickness to monitor these parameters over time. A meteorological station was installed to collect rainfall, air temperature, relative humidity, shortwave and longwave radiation, and wind speed and direction data. Two standpipe piezometers were installed and screened in native surficial deposits underlying waste rock. Additional instrumentation was installed at the Test Cover Trial site but is not described herein.



PLOT No.	DESIGN SLOPE ANGLE	RECLAMATION MATERIAL DESIGN THICKNESS (m)
01	ANGLE OF REPOSE	0.0
01 - TRANSITION	-	0.0
02	2.0H:1V	0.3
03	2.0H:1V	0.7
04	2.5H:1V	0.0, 0.3
05	2.5H:1V	0.3
06	2.5H:1V	0.7
06 - TRANSITION	-	0.7
07	2.5H:1V	0.7
07 - TRANSITION	-	0.7
08	2.5H:1V	1.0
09	3.0H:1V	0.7
10A	3.0H:1V	0.7
10B	3.0H:1V	0.7
10B - TRANSITION	-	0.7
11	4.0H:1V	0.7
12 - TRANSITION	-	0.7
12	4.0H:1V	0.7
13	N/A	0.7

Figure 3. Test Cover Trial reclamation cover material as-built plan.

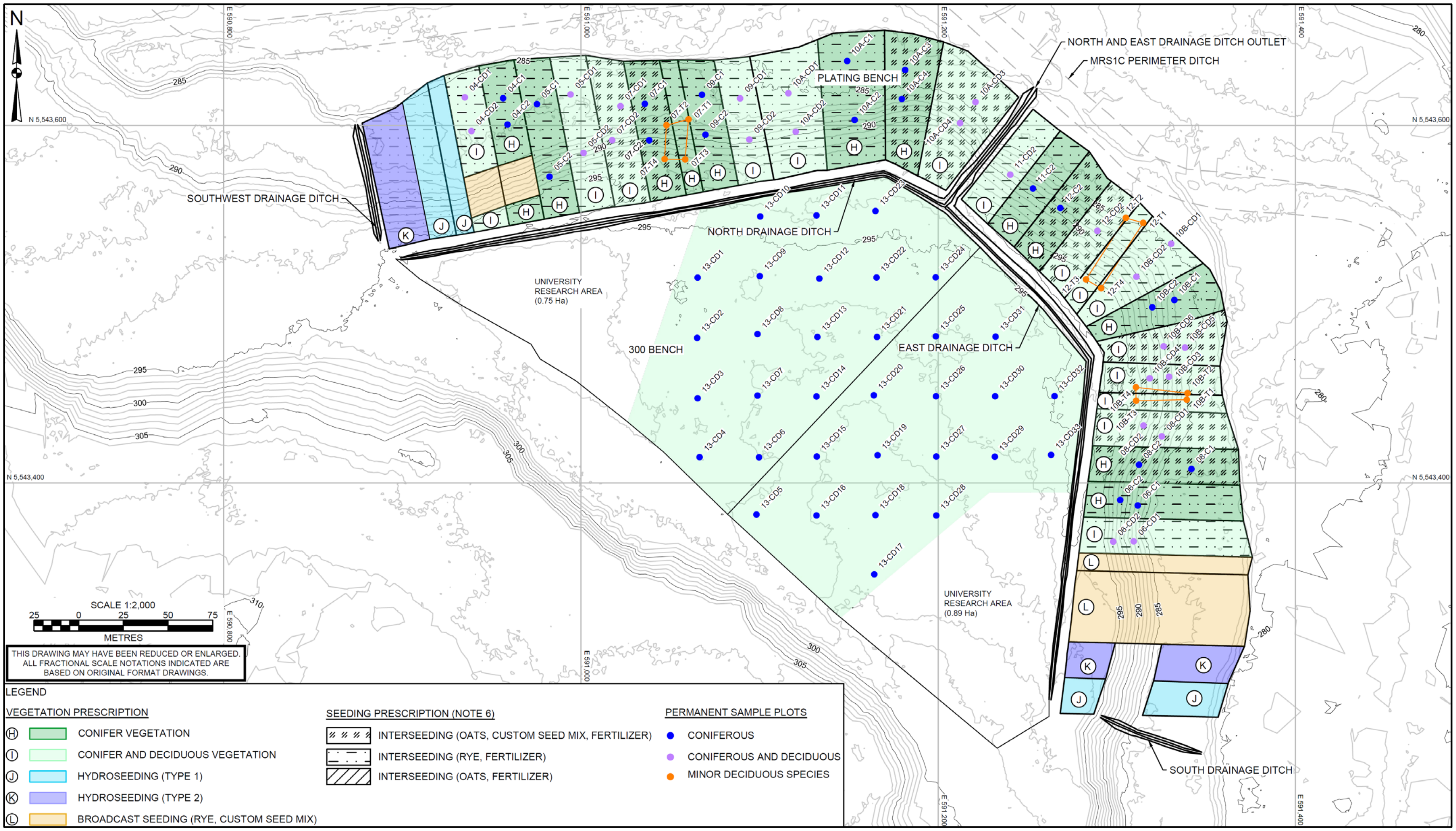


Figure 4. Test Cover Trial revegetation treatment as-built plan.

RESULTS AND DISCUSSION

Lessons Learned

The Test Cover Trial construction was the first mine-scale reclamation project that was completed at DLM. As a result, several insights into construction methods and techniques were gained throughout the construction process. The following provides a summary of lessons learned during the 2018 and 2019 construction seasons.

Waste rock slope regrading was challenging on slopes steeper than 2.5H:1V (22°). In general, regrading can alter the topography of slopes and benches and subtle changes in topography can affect surface drainage patterns after reclamation cover placement. As-built conditions also indicated that after regrading and cover placement, slopes were steeper than the design slopes. When placing reclamation cover material, 40-ton articulated haul trucks were able to back down waste rock slopes that were 4H:1V or flatter and could drive down waste rock slopes between 2.5H:1V to 3H:1V or flatter. These trucks could not drive on slopes with placed reclamation material due to a lack of traction. Similarly, during placement of the reclamation cover, surface contouring or trafficking on reclamation material with high water contents or where precipitation had recently fallen ranged from difficult to impossible. Wet reclamation material resulted in rutting, sliding of equipment and poor trafficability on the cover, and sliding and compaction of wet reclamation material.

As previously noted, loosening of the cover material was most successful using a ripping tooth on an excavator. The effects of ripping on net percolation, vegetation and erosion will be monitored over time and is discussed by Harrington et. al (2022).

Experience with vegetation installation in 2019 through seeding and planting indicated that seeding should occur as soon as possible after placement and/or loosening of reclamation materials. Early action helps establish vegetation quickly to contribute to control of surface erosion. Application of the custom native seed mix was challenging with handheld cyclone seeders due to the small size and light weight of these seeds, making the seeder prone to clogging. Dispersal was more effective when the native seed mix was blended 1:1 with either oats, rye, or fertilizer. Operators took care to homogenize the blend prior to seeding; however, blending could be conducted by the seed supplier prior to delivery.

Planting of container seedlings into denser materials, particularly with larger plug sizes, was difficult and resulted in leaning stems as it was challenging to excavate planting holes to adequate depths. This is one way in which higher-density cover material is limiting to reclamation. Productivity of tree planters was affected by the size of the deciduous seedlings (with large root plugs requiring larger and deeper excavations), and by site preparation. Larger plugs and denser materials resulted in reduced productivity, while the smaller plugs (conifer species) and ripped areas resulted in increased productivity. Managing the logistics of planting would be easier with a spring (cold-lift) planting of cold-stored seedlings, as planting is done with dormant vegetation, and this timing allows plants to take advantage of higher spring rooting-zone water contents during a period of high root growth and limited water demand from shoots (early in the growing season). Fall (hot-lift) planting is more challenging, as plants are not dormant and need to be watered. For fall planting, the timing of the second week of September worked well, as it allows plants some time for root growth prior to freezing conditions and avoids excessive water loss through active foliage. For fall planting of mine reclamation, deciduous seedlings should be cut back prior to shipping (i.e., to increase root:shoot ratios) to reduce water loss and transpiration stress after planting.

During the construction period, instrumentation installation lagged after cover placement by approximately two months. This lag was advantageous as some limited erosion of the reclamation cover had occurred, so instrumentation was installed in areas with less erosion such that instruments within the reclamation cover were not exposed.

Monitoring Program

After the completion of the 2019 construction program, ongoing monitoring campaigns were initiated to evaluate the relative performance of the Test Cover Trial plot designs and to collect data to support future interpretations and designs. The monitoring program includes data collection from the installed instrumentation, and visual observations of the geotechnical and vegetation performance. The companion paper by Harrington et al. (2022) describes preliminary results from monitoring that is ongoing to evaluate the performance of thirteen different trial treatments.

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