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Configuration of Mine Closure Landforms — Geomorphic Approach

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Abstract

Post-mining landform contouring is becoming an important consideration in mine planning and permitting in parts of North America. Regulators and stakeholders are becoming increasingly concerned about reclaimed landforms that fail to provide an appearance, ecological productivity, drainage effectiveness, perpetuating vegetation, and stability similar to natural, undisturbed landforms. Mine owners are also becoming concerned about the long-term liabilities associated with reclaiming mine-disturbed land that may be subject to accelerating rates of deterioration through weathering (leading to acid and metalliferous drainage), erosion and salt accumulation. Accordingly, techniques for replicating natural landforms and natural drainage systems are being developed to achieve similar composition, contouring, and hydrologic functions as undisturbed landforms. The geomorphic approach offers appropriate guidance to mine planners and engineers. In place of the typical geometric waste dump shapes with flat tops and homogenous benched sides, the geomorphic approach offers micro-topography provided by dendritic drainage courses with decreasing slopes at the base of the landform, mimicking mature natural landforms. A characteristic drainage density is provided to control overland flow path lengths. Landform slopes are selected to provide adequate drainage without causing excessive risks of erosion. Headwater drainage courses in mountain areas are composed of natural rock-lined channels. In non-mountainous areas, ephemeral drainage courses at headwater areas are frequently composed of vegetated waterways. Downstream of such headwater drainage courses, alluvial channels are built to mimic the regime relationships of equivalent natural systems and facilitate the rapid development of mature alluvial processes in constructed channels, by replicating key characteristics of natural systems that may exist nearby. Designers hope to achieve the type of long-term sustainability that is evident in most natural systems. Replicating natural landscape and natural drainage systems requires a sound understanding of rainfall patterns, evapotranspiration, surface cover and hydrology, hydrogeology, erosion, sedimentation, and fluvial geomorphology. Various principles for replicating natural systems have been developed for landform design and drainage on mine-disturbed land. Several examples of the geomorphic approach show how these principles have been applied to landforms in the oil sands region of Alberta and the coal mines in western Canada and Washington State. Preliminary findings of a large applied research study to develop techniques for replicating natural channels in northern Alberta are summarized.

1 Introduction

Typical waste dumps, tailings containments and mine pits at reclaimed mines consist of topography that is fairly uniform compared to natural land forms in the vicinity. Topography is frequently characterized by uniform slopes, linearity, benched slopes and large flat areas bounded by steep side slopes. The effects of surface water run-off, soil erosion and soil moisture are frequently overlooked. Drainage channels are often established without considering the natural evolution of a drainage course in response to erosion processes, despite the provision of hard armoring for erosion control.

McKenna and Dawson (1997) inspected fifty-seven abandoned and partially-reclaimed mines to determine the effectiveness of existing mine closure practices and performance of the reclaimed mine landform. Their findings show that a most significant risk to the landscapes is associated with surface water processes, particularly erosion. This is not surprising since natural landforms are largely formed by surface run-off.

Unlike natural landforms that have been subject to several millennia of change by natural erosion and sedimentation, constructed landforms are vulnerable to relatively high rates of erosion if the topography is not contoured to suit shapes that represent a dynamic equilibrium in natural systems.

Soil erosion is the most frequent cause of constructed landform and channel deterioration. Despite its seemingly slow rate, erosion represents a significant environmental risk following mine closure as a result of its progressive nature. Changes in landform configuration caused by soil erosion include slope failures due to erosion of vulnerable slopes, gullies that penetrate through protective covers, drainage channels that adjust to suit a new characteristic regime, and hillslope degradation. Drainage channels are often vulnerable to rapid rates of deterioration because of the concentration of flow and deficient erosion protection systems. Perhaps the most catastrophic impact of erosion is the breaching of dam embankments resulting in run-out of fluid and tailings materials. Erosion is a progressive phenomenon, of which the cumulative impact is governed by recurrent extreme hydrologic events. Studies have shown that erosion is episodic. Normal year-to-year landscape evolution may not be indicative of long-term trends.

There are many important considerations for the design of mine-disturbed landforms and drainage systems. These include regulations, stakeholder issues, geotechnical conditions, seepage and groundwater integration of wetlands and lakes, reclamation soils, revegetation and biodiversity.

This paper addresses hydrological controls that should be considered when planning the shape of surface topography and drainage channels of mine-disturbed landforms such as waste dumps, tailings disposal areas, and mine pit slopes. Findings presented herein are based on the authors' experience in designing closure landforms for coal mines in western Canada and Washington State, uranium mines in Saskatchewan and oil sands mines in north-eastern Alberta.

2 Planning for longevity

Erosion, landform evolution, landform performance and ecological productivity can be controlled by planning suitable topographic configurations and surface water conveyance systems. However, such planning must be conducted well in advance of landform development. The desired endpoints may be achieved economically if a detailed mine closure plan is carefully prepared during the initial stages of mine planning, when it may still be possible to provide the essential topographic features of the closure landscape.

Constructed landforms can be designed to suit a wide variety of land uses, a range of biological productivities, various ecosystems and various performance objectives. Topography and surface water conveyance are important controls that can be used in conjunction with soil cover material to control vegetation type, vegetation diversity, and wetland/lake/stream habitat as well as associated ecology. Wet landscape is commonly associated with large flat land that is poorly drained. Dry landscape is commonly associated with steeper slopes and a degree of relief that improves drainage and minimizes water logging.

A principal goal of landform and channel design should be to develop sustainable physical features of the landscape where rates of erosion are very low and comparable to those of natural landforms, where the risk of catastrophic failure is minimal, the landform configuration allows for a productive stable ecosystem, the watercourses support a productive aquatic environment, and maintenance is not essential or minimal. This goal is not always achievable. Nevertheless, it is prudent to target this goal to minimize the risk of rapid-mined landform degradation and minimize the level of maintenance that may be required to avoid serious degradation.

Landforms that are configured to suit hydrologic processes will exhibit significant non-uniformity with well-defined water courses located in incised valleys. The resulting variable relief benefits physical sustainability associated with hydrologic processes. There are other desirable features such as:

- Reduced line of site exposure, thereby offering protection for wildlife.
- An appearance that resembles natural systems.
- Vegetation diversity caused by variable soil moisture conditions, aspect and soil characteristics associated with variable topography.
- Flushing of salinity and prevention of widespread salt accumulation.

- A productive landscape by control of the water table (avoiding wetlands where productive forests are desired as well as creating wet areas where wetlands are required for flow attenuation, habitat and water quality remediation).

3 Constructed landform configurations that are vulnerable to failure

Until recent interventions by regulators, stakeholders, and some forward-thinking mining companies, mine-disturbed landforms have often been constructed primarily to minimize cost and inconvenience. Little consideration seems to have been given to hydrologic and geomorphic criteria that govern sustainability. The historical approach to configuring landscapes for reclamation was to develop uniform slopes conforming to neat lines, and grades complete with benches or terraces that were somehow expected to minimize erosion. Such design uniformity may not achieve the mine closure objectives of minimum erosion and long-term sustainability. Uniform landforms resemble an immature topography that may be poised to evolve by accelerated erosion.

Landforms that were constructed without attention to hydrologic and geomorphic processes may exhibit one or more of the following features that can lead to rapid or progressive deterioration of the constructed landscape.

3.1 Dams that impound fluid containments

A body of fluid that is contained by a relatively thin embankment, or membrane of constructed material, represents a significant long-term liability. The membrane is subject to material deterioration. An earthfill embankment is subject to breaching by erosion or overtopping. The equivalent to a dam and fluid containment in the natural environment is extremely rare because hydrologic and geomorphic processes, over long periods of time, have caused such features to fail. The exception is ponding behind bedrock outcrops. These have not failed because of the durability of the bedrock.

3.2 Benches or terraces on waste dump side slopes and other embankments

Benches and terraces result in high risk of large-scale gullying because they are vulnerable to ponding. Excessive ponding can cause spillage that occurs at a single point. This results in the formation of large gullies. Benches are also undesirable because they require higher slopes between benches, relative to the overall slope length of the facility. Higher slopes are more vulnerable to erosion, particularly at the toe of the waste dumps or other embankments.

3.3 Long uniform slopes

Long slopes are associated with long overland flow path lengths. The overland flow concentrates with increasing flow path length, and therefore the vulnerability to erosion and gullying, increases with overland flow path length.

3.4 Steep slopes particularly at the down-slope end of overland flow

Waste dumps with flat tops that drain over steep side slopes, are highly vulnerable to erosion because the steep slopes are exposed to high overland flows from the large flat top drainage area, resulting in higher overland flow velocities and higher associated rates of erosion.

4 Constructed watercourses that fail due to erosion

Despite the abundant illustration of stable watercourses in the natural environment, drainage designers have tended to analyze hydraulic processes that govern stability, paying little attention to the geomorphic processes at work in natural systems. The resulting hard engineering designs frequently deteriorate due to natural geomorphic processes, design flood exceedance, or unexpected conditions such as sediment accumulation, debris jams, beaver dams as well as snow and ice obstructions. Geomorphic processes have been overlooked in the following examples of traditional “hard” engineering approaches to channel design.

4.1 Hard armor lining designed for specific recurrence intervals

Rock armor channel lining commonly consists of a relatively thin layer of rock that is vulnerable to rapid failure in the event of design flood exceedance. Blockages by debris, ice, sediment or animal activity can lead to avulsions similar to overtopping due to design flood exceedances.

4.2 Shallow channels on uniform topography

In contrast to mature natural channels situated in deeply incised valleys, traditional engineered channels are often built in a shallow watercourse in compliance with the design flow depth, with little contingency in the event of a flow exceedance or flow obstruction. This results in spillage and channel relocation.

4.3 Straight prismatic channels

In contrast to meandering natural channels, with bedforms composed of chutes and pools, traditional engineered channels are often designed to replicate trapezoidal canals that have a uniform channel bed gradient. The canal is vulnerable to accelerated erosion as it attempts to readjust its planform to suit a natural characteristic meander pattern.

4.4 Lack of flood flow attenuation

Typically mine-disturbed land is composed of steeper terrain, reduced topographic complexity, channels without floodplains, an absence of lakes and wetlands, and thin cover layers of organic soil relative to predevelopment conditions. Without mitigation, such features result in higher flood peaks, reduced low flows, and reduced water retention to support vegetation. This normally results in higher rates of channel erosion.

4.5 Absence of vegetated watercourses

Whereas the natural environment benefits from vegetated water courses at headwater areas, many reclaimed mine environments do not utilize such systems to control erosion. Instead, traditional engineered watercourses may be lined with rock armor even at locations where vegetation could be used to avoid erosion.

5 Constraints on geomorphic landform design

There are a number of constraints that limit the scope of engineered landform shapes that might be conceived by the landform designer. Constraints include cost, lease boundaries, geotechnical stability, proximity to other facilities, and site access for monitoring and storage efficiency. Perhaps, the greatest constraint is the intransigence of planners and designers who resist change from traditional reclamation methods involving uniform slopes and benched embankments.

Cost is a very important constraint. It would not likely be economically feasible to rebuild an existing waste dump to suit a configuration that requires the relocation of large material volumes. Great cost savings can be realized by building the desired landform shape during construction, thereby avoiding the cost of reconstruction. There are also great cost savings associated with a landform configuration that suits the equipment and methods used to build the mine waste facility. A facility built by a dragline will assume a “saw-tooth”. A facility built by truck dumping will generally take the shape of a “mesa”, but could be built to any shape, including rolling hills matching the natural landform. Therefore, it is important for the designer to understand the construction methods, and their limitations, so that landform shapes can be developed at minimum cost and the appropriate selection of equipment can be made.

Lease boundaries and regulatory constraints are common.

Geotechnical slope stability criteria play a significant role in the overall slope and maximum local slope of a landform, particularly if the mine waste material is prone to loss of strength on weathering or flooding.

Site access for operations and monitoring require roads that suit benched embankments. However, eliminating benches may simply require the use of quads or snow mobiles for access, since these vehicles do not require graded access roads.

Storage efficiency is a common constraint at sites where there is limited area for waste dumps and out-of-pit tailings containments. The resulting footprint of out-of-pit facilities is required to be as small as possible. Irregular topography that suits hydrologic and geomorphic criteria requires a larger footprint, or else higher crest levels of waste dumps or tailings containments. An enlarged footprint or elevated crest level can translate to extra cost.

The geomorphic approach to landform shaping and channel design is subject to some risks during the conditioning period immediately following construction. Immature vegetation and construction imperfections can make newly-constructed facilities subject to accelerated erosion during the transition period after construction and before development of a mature landscape. Special measures such as temporary erosion control measures, sedimentation ponds, maintenance and minor reconstruction are commonly required during the transition period, while the landform vegetation matures and drainage channels become conditioned.

6 Recommended approach for assessing landform shape

The complexities and dynamics of landscape evolution involve various physical processes that are not fully understood. Nevertheless, the closure landscape must be composed of sustainable landforms that may evolve and degrade slowly, while at the same time meeting the goals of physical stability, containment of waste material, and various land use objectives. With an imperfect understanding of the physical processes, and an inability to predict future performance precisely, the landform designer needs to adopt an approach that accommodates the inherent uncertainties of an evolving landscape. Such an approach might include the following principles:

- Patterning landform configurations, including slope profiles in three dimensions, water course density and depth, etc. after natural analogues.
- Designing the landform with multiple lines of defense against failure modes.
- Designing robust landforms where the landform self-heals and/or becomes more stable with time.
- Designing conservatively using proven technology where available.
- Avoiding the use of man-made materials that are subject to deterioration.

Required shapes of mine-disturbed landforms cannot be established by a literature review. Design parameters governing landform shape and configuration depend on a complex interaction of local climate, vegetation cover, surficial geology, soil conditions, seepage conditions, groundwater quality, aspect and scale. Several approaches can be adopted to develop landform design parameters as discussed below.

6.1 Replication of natural analogues

There are many natural full-scale models that have been tested over a long period of hydrologic events since the last ice age. Therefore, natural systems offer a wealth of data that may be directly applicable to the configuration of mine-disturbed landforms. Design parameters related to erodibility, vegetated water courses, drainage density, and maximum overland flow path length can often be derived by field/mapping investigation of natural analogues. The natural terrain in the vicinity of the mine-disturbed landform can often be emulated because these features are often governed largely by the ground surface condition, i.e. rainfall, snowmelt, surface soil condition, infiltration rate, and vegetation cover. Natural analogues may not be useful for determining the location of the groundwater table, predicting seepage discharge or for assessing the soil salinization potential, because these features are site phenomena that depend on the specific material characteristics of the mine-altered waste materials.

6.2 Analysis and modeling

The analysis and modeling of physical processes is often useful to estimate worst case and best case scenarios for a mine-disturbed landform. They require extensive data such as infiltration rates, hydraulic conductivities, dispersion coefficients, root mass, etc., many of which are poorly known. Analysis and modeling are applicable to assessing groundwater table conditions, seepage conditions and the potential for soil salinization. The problem of soil salinization and high water tables is associated with flat land, i.e. less than 0.5% slope in the Alberta oil sand region. Local water tables rise to the surface where the relief is insufficient to allow excess water to run off. Landform design parameters, to prevent soil salinization and to control the location of the groundwater table, are best derived by hydrogeologic analysis and confirmed by full-scale pilot testing.

6.3 Pilot testing and monitoring of constructed landforms

Pilot testing and monitoring of constructed mine-disturbed landforms are valuable for confirming and optimizing design parameters. Instrumented watersheds at reclaimed areas will provide valuable information for assessing the sustainability of landforms and for determining the need for incremental changes to design parameters.

7 Features of natural landforms in Alberta

Natural landforms are generally very well configured and equipped to minimize erosion. This results from a long exposure to the local environment and natural erosion processes. The long sequence of hydrological events, since the last ice age have allowed landforms to evolve to a state of dynamic equilibrium characterized by a low rate of erosion. Low rates of erosion are achieved by various processes, conditions, and features of natural landforms, as follows:

- A ground surface condition that resists erosion (i.e. vegetation cover in wet climates; crustations, rock armor, obstructions in dry climates, where the soil does not support a sufficient vegetation cover to resist erosion).
- Flood flow attenuation that is achieved by moisture storage in surface soils, and water storage in wetlands, lakes, and floodplains.
- Short overland flow path lengths where the topography is steep.
- No embankments or ponding on terraces that might spill catastrophically.
- Characteristic drainage density that suits the local soil erodibility and magnitude of erosion-producing events.

Natural terrain at the Alberta Oil Sands Region (OSR) is composed of large areas of muskeg and relatively thick layers of peat. Upland or well-drained areas generally have a basin slope greater than 0.5%, and lowland or poorly-drained areas have a basin slope of less than 0.5%. Poor drainage is a result of shallow slopes above an underlying layer of relatively impermeable glacial and glaciolacustrine clay. In combination with the accumulation of vegetation under saturated conditions, this has resulted in the development of highly-organic muskeg soils and associated plant life. The cohesive nature of muskeg likely plays a significant role in influencing the morphology of many stream channels in the OSR. Additionally, the poor drainage through muskeg terrain allows it to attenuate the regional hydrological response to hydroclimatic events (e.g. snowmelt and rainfall). These natural conditions are associated with very slow rates of erosion and relatively uniform streamflow conditions that may support a superior aquatic habitat.

Natural landforms might generally be considered maintenance-free because ongoing erosion is usually considered acceptable in the absence of infrastructure and other man-made developments. Likewise, the goal of the landform design may be to develop a reclaimed landscape that does not require perpetual maintenance, just like natural landforms.

Figure 1 illustrates non-uniformity of natural terrain with a vegetated watercourse that exhibits self-perpetuating vegetative cover.

Figure 1 Natural vegetated water course in Southern Alberta that serves as a basis for replication at constructed landforms

8 Features of natural alluvial channels in Alberta

Natural alluvial channels in the OSR can be classified as upland or lowland channels. The upland channels are steeper, have a low sinuosity and the flows in them are typically intermittent. The lowland channels are located in the flat lowland areas and exhibit more sinuous patterns. The OSR is heavily forested and is subject to woody debris inputs to streams from various sources (e.g. chronic tree mortality, wind throw, beaver activity) that can significantly influence channel morphology. The prevalence of beaver activity in the lowland areas leads to considerable changes to stream morphology. Active and inactive beaver dams divert and back up stream flow, increasing the natural variability in bank full width and depth. The attenuation of flows by muskeg, and the damming of flows by significant wooden debris and beaver dams, result in slow continuous moving flows in the lowland channels.

Regime relationships that describe channel dimensions in terms of governing parameters – i.e. channel gradient, bank full discharge and bed/bank material – were derived for bank full width and bank full depth based on a two-year field data monitoring programme in the OSR. The results were compared to equivalent regime relationships in the literature. The results indicate that exponents for bank full discharge are within the range reported in the literature. The coefficients for bank full discharge are on the upper end of those reported in equations for bank full width and bank full depth, which suggests that channels in the OSR are generally wider and deeper than other channels for which regime relationships have been developed. This reinforces the need to collect site-specific data for a geomorphic design approach.

9 Recommended practices and derivation of design criteria

The development of sustainable landforms for mine closure should involve the design of landforms that replicate natural landforms to minimize the rate and risk of accelerated erosion and develop self-healing erosion control systems. Constructed landforms composed of erodable soils should be patterned after natural analogues that represent mature topography. Mature landform topography can be characterized by relatively short, steep slope lengths occurring in headwater areas, with slopes becoming gentler as flow concentrates in the downslope direction. The degree of topographic irregularity, or amount of relief, varies depending on its original state, soil erodibility, climate factors, soil conditions and vegetation.

The following erosion control parameters, which can be readily obtained by a field/mapping study of natural analogues in the vicinity of the mine-disturbed land, should be implemented in addition to avoiding landform and channel configurations that are vulnerable to failure, as described above.

- *Topographic irregularity (relief):* The required amount of topographic irregularity or relief is best derived by assessing the amount of relief exhibited by local natural landforms with the same soils, overall slopes, surface geology, groundwater conditions, vegetation and climate. The amount of relief can be analyzed by GIS, using a combination of parameters to represent relief. These should include irregularity measures such as “depth of swales” and “contour departures from straight lines”. The latter would be referenced to a range of distances (departure per 100 m, 200 m, 500 m, etc.) depending on the overall uniformity of the landform. Figure 2 shows a waste dump that was built with topographic irregularity similar to natural terrain.
- *Drainage density:* There is a characteristic drainage density that depends on typical slope conditions in the watershed, local climate, surface soil conditions, surficial geology and vegetation (Schumm, 1977). Most of these parameters can be taken into account by considering a single geographic area with similar physiographic and climate conditions. Slope then becomes a governing variable. In such cases, drainage density can be derived as a function of slope based on topographic data for a given region. The drainage density of the reclaimed landform should equal or exceed the drainage density of natural analogues. The depth of constructed drains should also match natural water course depths. Figure 3 shows a constructed waste dump with built-in drainage density characteristic of nearby natural terrain.
- *Maximum overland flow path length (MOFPL):* The maximum allowable overland flow path length (MOFPL) is a landform characteristic that, like drainage density, depends on various factors such as climate, soil type, surface geology, slope and vegetation cover. It can be estimated based on large-scale maps that show all watercourses. A plot of MOFPL against terminal slope generates a scatter diagram that often forms a unique envelope curve. Exceeding the MOFPL in the constructed landform will likely result in gullying. Applying a 25% safety allowance to the threshold condition, as indicated by the envelope curve, is prudent.
- *Vegetated water courses:* Where a dense vegetation cover is sustainable, vegetated watercourses should be used in swales of hillslopes because they are very effective for controlling erosion. Vegetated watercourses are constructed differently from vegetated hillslopes. A study of naturally occurring vegetated watercourses (Golder, 2004) shows that typical natural vegetated watercourses have relatively large bottom widths. They have a flat base that distributes the flow over a wide area. The important distinction of a vegetated watercourse is the large depth of organic soil (> 0.8 m) that absorbs water to provide a suitable reservoir of soil moisture that allows the vegetation to flourish through a dry season. Detailed investigation and design procedures for vegetated watercourses were derived for OSR (Golder, 2004). Figure 4 shows a constructed vegetated watercourse on a waste dump composed of relatively impervious overburden material.

Figure 2 Irregular topography built into an overburden waste dump in East-Central Alberta

Figure 3 Vegetated swales built into an overburden waste dump at a coal mine in Washington State

Figure 4 Mature vegetated water course at an overburden storage area in Northern Alberta

- *Ponding on terraces:* A common misunderstanding is that terraces prevent erosion. Although terraces intercept surface run-off during low-intensity storms, erosion can only be controlled if the accumulation of surface water does not exceed the storage capacity on the terrace or if the resulting spillage is properly controlled by a spillway structure. Whereas terraces without spill structures can prevent erosion in the short term during normal hydrologic events, they cause accelerated erosion during extreme events when their storage capacity is exceeded. The erosion damage caused by such uncontrolled spills can be very severe, as illustrated by the many failures in tropical terraced agriculture, and several notable failures of mine-disturbed landforms. Further, terraces exacerbate the piping erosion of dispersive cover soils. Terracing represents immature topography and is not well represented in nature as an erosion control mechanism. Terraces should therefore be avoided if possible. They should be tipped out by at least 3% slope if it is impossible to avoid terraces, provided that the overall slope length is consistent with the maximum overland flow path length for the region and slope condition.
- *Geomorphic design of drainage channels:* Drainage systems should be designed to accommodate gradual change over geological time frames, and sediment yield from reclaimed surfaces should be comparable to that from natural systems. Drainage systems should be designed to achieve comparable robustness, self-healing capability and longevity to natural systems. Instead of providing channel armoring in an attempt to develop a fixed conveyance system, the landform designer should incorporate regime channels that replicate the dynamic character of natural channels. Some examples of natural channel features include meanders, channel dimensions that conform to regime relationships, floodplains, and reserve sources of armor material for re-armoring channels where armor has been removed by scour. Natural channel characteristics may be assessed based on field measurements of channel parameters that include channel depth, slope, width, sinuosity, meander wave length, and width-to-depth ratio. The resulting regime channels that are patterned after natural channel characteristics will exhibit equilibrium conditions, avoid rapid progressive channel degradation or aggradations, and handle extreme events. Flow capacity can be achieved by building drainage channels in well-defined swales or small valleys, just like natural drainage systems. The designer should replicate natural systems where streams are flanked by floodplains that attenuate

flood flows and reduce channel velocities. Also, wetlands and lakes should be provided for flood attenuation as part of closure drainage systems to mitigate loss of natural terrain that attenuates flows in pre-disturbed areas.

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