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Geomorphic design of alluvial channels for oil sands mine closure

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Abstract

The design of mine closure alluvial channels in the Oil Sands Region (OSR) is typically based on the geomorphic approach which requires an understanding and characterisation of natural alluvial channels in the region for replication at mine closure. In 2005 and 2006, detailed geomorphic surveys were conducted at 54 representative stream reaches to collect channel dimensions, channel slope, sinuosity, bed material composition and instantaneous discharge. This dataset was augmented with data available in oil sands environmental reports and regional maps; and flow modelling results of the selected stream reaches and their basins.

The resulting dataset was used to produce region-specific regime relationships relating dependent reach-averaged channel parameters for width, depth and slope to discharge. Relationships were also provided to reflect the variations in channel variable within a reach, and recommendations were provided for meander wavelength and meander belt width. Roughness caused by large woody debris and other obstructions such as active and inactive beaver dams was determined to have a significant effect on channel morphology. This effect can be mimicked, prior to beaver colonisation, by placing roughness elements across the constructed channels at specified intervals using a design tool developed for this purpose.

A step by step design procedure for replicating natural analogues or using the regime approach is provided to assist in designing alluvial channels in OSR mine closure landscape.

1 Introduction

Bitumen reserves in the Athabasca oil sands region (OSR) operations involve large land disturbances typically exceeding 50 km^2. The large extent of excavations and fill placement often requires diversion of major watercourses and disturbance to the landscape and surficial geology. This results in new topography and drainage patterns at the end of mine operations that are expected by regulators to accommodate a wide range of hydroclimatic events without failure and damage to the receiving ecosystem. Regulations require oil sands mine closure diversion and drainage systems to be conceptually planned and designed well before commencement of mining activities, with updates required every five or ten years.

The traditional approach to mine closure drainage design is the structural approach which is based on a design flood event with a specific recurrence interval. Accordingly, partial or complete failure would be deemed inevitable during extreme events that exceed the design criteria. Features of this mine closure landscape such as uniform channel slopes, benches or terraces on earthfill structures and straight channels are typically rigid and require perpetual maintenance, in contrast to the surrounding natural landscape. The alternative to rigid systems is a geomorphic system which mimics the regional natural drainage systems. Natural drainage systems have matured and developed an equilibrium state that accommodates a wide range of typical and extreme hydrologic conditions without accelerated erosion or unacceptable environmental impacts. Constructed drainage systems that are built to replicate natural drainage are expected to involve minimal maintenance during the reclamation period and no maintenance following a conditioning period of several decades.

Replication of natural drainage systems in the OSR requires the collection and analysis of geomorphic data that capture the natural variability of physical stream characteristics including channel width and depth, sinuosity, slope, bed material size, pools and riffles, meander belt width and channel roughness. Detailed geomorphic surveys were conducted at 54 representative stream reaches over a period of two years. This dataset was augmented with data available in oil sands environmental reports and regional maps; and flow modelling results of the selected stream reaches and their basins. The resulting dataset was used to produce region-specific regime relationships relating reach-averaged channel parameters for width, depth and slope to discharge. Relationships were also provided to reflect the variations in channel variable within a reach, and recommendations were provided for meander wavelength and meander belt width. Existing regime relationships available in the literature are based on different climatic, geologic, physiographic and hydrologic conditions and are not applicable to the OSR.

It is recommended that geomorphic design of mine closure drainage should be approached in two ways, either through the "analogue" design approach or the regime equation approach. The former approach requires that the characteristics of a nearby natural channel be replicated in a new location or reclamation area, based on comparable terrain, sediment transport and hydrology. In circumstances, where no natural analogue stream can be found that meets the required criteria, a step-by-step process must be followed in which regime relationships based on local data for relevant key channel parameters are used to design streams.

2 Physical setting of the Athabasca oil sands region

The regional climate of the Athabasca OSR varies between humid continental and sub-arctic with long, very cold winters and short, warm summers. Environment Canada climate data dating to 1950 indicate that average temperatures at Fort McMurray range from -18.8° C in January to +16.8° C in July. Total annual precipitation is approximately 456 mm, of which 342 mm falls as rain in the summer and 156 cm falls as snow.

The OSR is heavily vegetated by boreal forest tree, shrub, and grass species. Peat (muskeg) accumulations occur in lowland areas where the hydraulic gradient is small and relatively impervious mineral soils are present beneath the organic accumulations. Boreal forest vegetation occurs in upland and lowland areas but does not occur on muskeg accumulations. The surficial geology includes glacial till plains and moraines, glaciofluvial sands and gravels and glaciolacustrine clay and silt.

The regional hydrology is strongly influenced by upland and lowland areas that have distinctive effects on channel form and response to hydrological events. Vegetation, muskeg terrain, large quantity of woody debris in the streams and beaver activities contribute to the unique hydrologic conditions. Spring snowmelt and summer rainfall runoff events control the hydrograph responses and typical annual runoff values for the basins vary from about 50 mm to 135 mm.

3 Alluvial channels

OSR alluvial channels can be characterised as upland or lowland channels and by the boreal forest or muskeg vegetation surrounding them. Other characteristics include the sediment load, amount of beaver activity, sinuosity, and riffles and pools. The figure below shows typical OSR alluvial channels. Upland alluvial channels typically have a slope between 0.5% and 5% and therefore not attractive to beavers due to the reduced potential for developing a pond. The channel flow is faster and the bed material may be composed of permeable gravels, cobbles and material as large as boulders. Upland areas are usually forested due to the drier soil conditions.

Figure 1 Left: upland channel with cobble-sized bed material; right: lowland channel flowing through muskeg

Lowland streams have slopes less than 0.5 % and are influenced by beaver activities. The channel flow is impeded by beaver dams, fallen trees, debris accumulations, form resistance features resulting from irregular channel bed and banks associated with muskeg accumulations and shallow hydraulic gradients. Sediment load is typically low due to these features and the negligible sediment inputs from the lowland area that is vegetated with low grasses and shrubs.

4 Regime relationships

Alluvial stream channels that replicate natural systems can be designed based on regional regime relationships derived from fluvial geomorphic data including bankfull flow width and depth, channel slope, sinuosity, bankfull flow, sediment size, roughness, meander belt width and meander wavelength. These relationships typically relate dependent channel parameters for width, depth and channel slope to controlling discharge and channel roughness parameters. Existing regime relationships available in the literature are based on different climatic, geologic, physiographic and hydrologic conditions and are not applicable to the OSR.

Total E&P Canada (Total) participated in a geomorphic research study conducted by the Environmental and Reclamation Research Group (ERRG) of Canadian Oilsands Network for Research and Development (CONRAD). Geomorphic data collected during this research study and available data collected during various Environmental Impact Assessments (EIAs) of oil sands developments were used to develop a geomorphic database for the OSR. The research study involved a survey of 54 representative stream reaches including a variety of creek sizes, upland and lowland streams, and creeks located in a variety of geological conditions (CONRAD, 2008a, 2008b). At each survey stream reach, typically 20 times the bankfull width (about 60 to 120 m in length), data were collected at three to five cross-sections.

The resulting dataset was used to produce region-specific regime relationships relating reach-averaged mean and maximum bankfull depths, bankfull width, sinuosity and slope to discharge. Relationships were also provided to reflect the variations in channel variable within a reach, and recommendations were provided for meander wavelength and meander belt width. The regime relationships, shown in the table below, are expressed as power equations with the independent parameter represented by the channel parameter and the dependent parameter represented by the bankfull discharge.

Table 1 OSR-specific regime equations for bankfull width and depth

Channel Variable	Reach-Averaged Regime Equations
Bankfull width, B_{bf}	$4.2Q_{bf}^{0.43}$
Maximum bankfull depth, $h_{bf\,\max}$	$0.60Q_{bf}^{0.38}$
Mean bankfull depth, $\bar{h}_{bf}$	$0.43Q_{bf}^{0.40}$

Q_{bf} is the bankfull discharge, assumed to be equal to the 2-year flood discharge.

The coefficients and exponents of the OSR regime relationships are comparable to those in the literature; however, channels in the OSR are observed to be typically wider and deeper than those expressed by published regime relationships. Uncertainty in the results of reach-averaged data analysis was quantified by applying 75% confidence limits to the regime data. Exceedance curves were also prepared to show the variability of channel dimensions and the percent of time a given deviation from the reach-averaged channel parameter value occurs. Exceedance curves were prepared for sinuosity, mean bankfull depth, maximum bankfull depth and bankfull width.

A relationship between channel slope and bankfull discharge, augmented by data from the literature, indicates that there is a channel slope threshold for sands and finer materials based on the representative bed material size. Relationships were also proposed for meander belt width, meander wavelength and sinuosity. Suggested approach to mimicking the channel roughness due to large woody debris and other obstructions was by placing roughness elements (obstructions made of naturally-occurring debris) in the constructed channel at intervals determined using a design tool developed for this purpose.

4.1 Limitations of OSR regime equations

The geomorphic data used to develop the OSR-specific regime relationships were collected at streams that are of similar size to those that are anticipated to be present on reclamation landscapes in the OSR. The majority of the data was obtained from streams with drainage areas less than 150 km^2, channel slopes less than 0.75% and associated bankfull discharges less than 10 m^3/s.

Use of the regime equations and relationships to design streams in the OSR beyond the suggested thresholds is not recommended and could lead to catastrophic channel failure, significant environmental damage and economic loss.

5 Design methodology

5.1 Applicability

Oil sands mine-disturbed areas are made up of unique features that are not present in the natural environment in the OSR. They typically include cleared areas, consolidated areas (e.g. plant site and dyke surfaces), overburden capped in-pit tailings areas, sand storage areas, in-pit and out-of-pit overburden disposal areas, coke storage areas and pit lakes. The geomorphic approach could be applied to some of these areas depending on the landform configuration and methods employed to achieve the geomorphic condition. Where possible, potentially vulnerable landforms, such as those composed of coke, unconsolidated overburden materials or tailings, should be situated at the headwaters of the watershed where relatively short overland flow path lengths promote drainage by sheet flow and vegetated water courses offer equal or better opportunity for maintenance-free function. Design for OSR vegetated watercourse is presented in Golder (2004).

The geomorphic approach can be effectively applied to the development of low-gradient perimeter channels at the toe of embankments, and on undisturbed or cleared terrain at the perimeter of the mine and within the mine. Channels should be routed to areas where the underlying soils are suitably consolidated, slopes are relatively small and surface soil cover supports healthy natural vegetation.

The development of alluvial channels on large, flat areas composed of unconsolidated fine tailings will require a special application of the geomorphic approach. Placement of capping material should be controlled to form an undulating surface with topographic relief resembling a dendritic drainage pattern with ridges and swales. There should be enough capping in the low-lying areas (swales) to prevent erosion into the soft tailings during development of alluvial channels. Channels will be allowed to form in the swales by allowing natural erosive processes to shape the channels. Large sediment yields resulting from the self-forming channels will be contained in shallow wetlands and possibly in the pit lake. Sediment will not be released to the natural environment during development of these channels.

5.2 Design considerations

Mine closure drainage plans should replicate many of the features of the natural drainage systems that currently exist in the OSR. These features contribute to the sustainability of the natural channels and should be considered in geomorphic channel design. Design features to be considered include:

- Vegetated channels in the upper portions of a drainage basin to provide excellent erosion protection, increased flow resistance and unconcentrated flow path.
- Armor on the channel bed of steeply graded streams as this governs channel hydraulics, erosion control and channel morphology.
- Adequately sized channels to convey bankfull discharge (considering basin size and land types) and accommodate the high roughness and associated flow depths and widths resulting from blockages by debris and beaver dams.
- Adequately sized floodplains to convey floods as a result of numerous beaver dams and debris accumulations along the length of the channel.
- Deep channel/valley depth (at least 4m) in locations where beaver dams are not desired.
- Riffles and pools.
- Passive erosion control features (bed and bank material, bank vegetation, natural channel obstructions like debris, beaver activity and geometric irregularity).
- Suitable fish habitat in channel and connectivity to adjacent systems for all fish species that are intended to populate the system.

Unsustainable features that should be avoided in mine closure landscape include terraces and benches, dams, channels that are situated parallel to contours and channels equipped with rip-rap designed for a specific flood recurrence interval.

5.3 Analogue design approach

The analogue design approach involves replicating the characteristics of a nearby natural channel (analogue channel) at a new location, based on comparable terrain, sediment transport and hydrological equilibrium. The analogue stream provides a basis for recreating a stable channel morphology that has reached the desired dynamic equilibrium of natural channels; however, the channel designer must make certain that all of the governing features of the analogue channel are replicated as closely as possible. It is always preferable to use the analogue approach to replicate the characteristics of an existing, comparable geomorphic channel. However, the analogue approach may not be commonly used because of the anticipated absence of suitable analogues for a given channel site.

The following steps are suggested for the analogue channel design approach:

Determine the following information on the design channel to identify a suitable analogue channel:

- Design channel valley route and approximate meander channel belt width.
- Channel valley profile.
- Sections (sub-reaches) of the design channel with uniform flow and channel parameters.

- Channel bed and bank material composition.
- Watershed parameters including drainage area, upland area, lowland area, upland area to lowland area ratio, land type, land use, vegetation and surficial geology.

Search for an analogue channel in the region that has comparable features to those at the location of the design channel. If an analogue channel cannot be found, use the empirical design approach described below.

Conduct a geomorphic survey of the analogue channel by doing the following activities:

- Survey the channel cross section, water level and floodplain at several representative locations in the selected channel reach.
- Survey channel valley profile.
- Record bed and bank material at each survey location.
- Survey significant flow obstructions like large woody debris and beaver dams to note their location, configuration and influence on the flow conditions upstream and downstream.
- Photograph the site and its features.

Design channel based on survey data replicating the governing features of the analogue channel and adjusting for local conditions. The overall morphology should have the equivalent appearance and geomorphic function of the analogue channel.

5.4 Empirical design approach

The empirical approach to natural channel design uses regional sets of equations that relate channel characteristics to stream discharge and also assumes equilibrium hydrologic and sediment transport conditions. The empirical approach is similar to the analogue approach in that it uses measured data for channel design, but it uses the mean characteristics of a large dataset rather than a single analogue. Channel variables can be determined using empirical relationships from relatively few known variables. The following steps are suggested for the empirical channel design approach.

Bankfull discharge: determine the channel bankfull discharge (assumes equal to the 2-year flood discharge) based on historical flow data from a hydrologically similar gauged basin or simulated flow data from an OSR-calibrated hydrologic model (e.g. HSPF model calibrated for the OSR (Golder, 2003)), or available flood discharge versus drainage area charts.

Sinuosity and channel slope: determine the range of sinuosity from the OSR channel regime sinuosity relationship by finding the sinuosities that correspond with the upper and lower confidence limits at the determined bankfull discharge. Establish the valley alignment and calculate the valley slope. The range of bed channel slope can then be determined from the following equation. Select the channel slope within this range that best suits the topographic conditions. The sinuosity associated with this value should be considered as the reach-averaged sinuosity for the design process.

$$Slope_{channel} = \frac{Slope_{valley}}{Sinuosity}$$

Bed stability: based on the established OSR channel slope threshold relationship for sands and finer materials (Section 4), determine if the channel bed would be stable based on the expected representative size (D50) of the anticipated bed material based on surficial geology for undisturbed areas and material composition of constructed landforms. If the channel bed is unstable, reduce the valley slope by deepening the cut or changing the channel route; or increase the reach-averaged sinuosity; or introduce coarser bed material to achieve stable channel.

Macro channel sizing: Use the bankfull discharge established in Step 1 to determine the corresponding reach-averaged bankfull width, maximum bankfull depth and mean bankfull depth from the equations in Table 1. Determine the ranges of meander wavelength, meander belt width and floodplain width based on

OSR regime relationships. Determine the size and spacing of the roughness channel obstructions using a design tool developed for this purpose.

Micro channel sizing: channel size variability along the design channel reach is determined using exceedance curves developed from OSR data. Exceedance curves were used to determine the ranges of deviations from the reach-averaged value of sinuosity, mean bankfull depth, maximum bankfull depth and bankfull width. Deviations from the reach-averaged value of sinuosity, based on OSR measured data, range from -30% to +50% and for bankfull depth and width, the range is ±30%.

Channel alignment and form: establish the channel alignment and form incorporating the variations in sinuosity, bankfull depth and bankfull width. The deepest pools should occur where the meander bends are tightest (i.e. the radius of curvature is smallest) and vice versa. Pools must be placed at meander bends and riffles at inflection points between successive meanders. Place roughness elements appropriately (e.g. at the downstream end of pools) and adjust individual locations to comply with this natural occurrence.

Verify key channel design parameters: verify that the averages of the bankfull widths, bankfull depths and sinuosities along the design channel reach agree with the reach-averaged channel values indicated by the OSR regime relationships.

6 Application of geomorphic approach in OSR

Implementing geomorphic design in the OSR will take time considering that a typical mine development has a size of about 60–100 km^2 and a life span of over 20 years. This relatively new approach requires higher up-front costs and resources in design and heavy equipment construction of geomorphic channels. However, the long-term payoff is significant which includes reduced ongoing costs for maintenance, as well as legal liability.

The geomorphic approach methodology suggested above has been applied in preparing conceptual closure drainage plans for a number of oil sands mine developments including Total's Joslyn North Mine. In addition, it has also been applied in the design of the Joslyn Creek Realignment.

References

Canadian Oil Sands Network for Research and Development and Department of Fisheries and Oceans (CONRAD) (2008a) Geomorphic Characterization and Design of Alluvial Channels in the Athabasca Oil Sands Region, Prepared by Golder Associates Ltd., Calgary, Canada.

Canadian Oil Sands Network for Research and Development and Department of Fisheries and Oceans (CONRAD) (2008b) Alluvial Channel Design Manual Procedures for the Athabasca Oil Sands Region, Prepared by Golder Associates Ltd., Calgary, Canada.

Golder Associates Ltd. (2003) Regional surface water hydrology study for re-calibration of HSPF model, Submitted to Canadian Natural Resources Limited, Shell Canada Limited, Suncor Energy Inc., Syncrude Canada Ltd.

Golder Associates Ltd. (2004) Vegetated Waterways Design Guidelines, submitted to Syncrude Canada Ltd.