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Development of a technical guidance document for cover system design in cold regions

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Abstract

The Contaminated Sites Programme of Indian and Northern Affairs Canada (INAC-CSP) is responsible for closure of contaminated sites on Crown land throughout the Canadian North. A significant percentage of the closure liabilities faced by Indian and Northern Affairs Canada (INAC) is associated with abandoned mines. Of these mine-related liabilities, at least one third involve the need to construct earthen cover systems over potentially reactive tailings and waste rock. INAC will be implementing cover systems at some sites in the very near future and therefore requires information on key physical, chemical, and biological processes that may affect long-term risk to these cover systems. This paper describes the technical guidance approach for cover systems in cold regions that is being developed by INAC with the assistance of a Technical Advisory Group (TAG). The focus of the paper is on the cover system design philosophy including the need to develop site specific closure objectives and criteria, mine closure planning and progressive reclamation, utilising attributes of cold regions, designing for sustainability, importance of final landform design, and assessment period and design life.

1 Introduction

Mine waste such as tailings or waste rock typically contains sulphide or other minerals, which can generate drainage with elevated metals and other contaminants of concern. As such, deposits of tailings and waste rock need to be dealt with in an appropriate manner as part of closing or reclaiming a mine site. In the case of acid-generating waste material, the preferred closure option is generally disposal of the waste material below the water table to limit further oxidation of sulphidic minerals e.g. disposal in an abandoned open pit. However, this is not a feasible option at many abandoned sites, particularly in the north, due mainly to cost considerations. Therefore, the closure option for most above-grade deposits of tailings or waste rock generally involves construction of a 'dry' or soil cover system.

The primary purpose of placing soil cover systems over reactive waste material is to minimise further degradation of the receiving environment following closure of the waste storage facility. This is achieved in most cases by reducing the net infiltration of meteoric water to attenuate peak concentrations for contaminants of concern in natural watercourses, to levels that can be assimilated without adverse impact to the aquatic ecosystem. In addition to contaminant release control, cover systems can also provide chemical and physical stabilisation of waste material and a growth medium for the establishment of a sustainable vegetation canopy. Apart from these functions, cover systems are also expected to have minimal erosion and be a key component of a sustainable final landform. Soil cover systems can be simple or complex, ranging from a single layer of earthen material to several layers of different material types, including native soils, non-reactive tailings and/or waste rock, geosynthetic materials, and oxygen consuming materials (MEND 2.21.4, 2004).

The Contaminated Sites Programme of Indian and Northern Affairs Canada (INAC-CSP) is responsible for remediation of contaminated sites on Crown land throughout the Canadian North. A significant percentage of the remediation liabilities faced by Indian and Northern Affairs Canada (INAC) are associated with abandoned mines. Of these mine-related liabilities, at least one third involve the need to construct soil (earthen) covers over reactive tailings and waste rock.

INAC anticipates that cover systems will be implemented at some sites in the very near future, and therefore require additional information on key physical, chemical, and biological processes that affect long-term risk to these cover systems. The appropriate design and long-term effectiveness of earthen covers in cold regions is therefore of central importance to INAC, as well as to local and regional stakeholders.

The Mine Environment Neutral Drainage programme (MEND) recently completed a Phase 1 review of soil covers on mine wastes in cold regions (MEND 1.61.5a, 2009). Several dozen cold regions processes were identified as potentially significant for soil covers. The most widespread are ground freezing and ground ice formation, ground thawing and associated settlement, and freeze-thaw cycling. Combinations of these processes with specific soil or hydrologic conditions can change soil properties, such as compaction and permeability, or lead to the development of macroscopic features, such as solifluction, cracking, mounding or hummocks, or mudboils. These effects can develop slowly enough that they may not be obvious in current observations of soil covers, but quickly enough that they might have significant effects over a cover's design life.

Following on the findings and conclusions of MEND 1.61.5a (2009), Phase 2 of the study was undertaken (MEND 1.61.5b, 2010), which involved various tasks in support of advancing the state of cold regions cover research. These tasks included:

- Cold regions phenomena identified in the Phase 1 report were characterised as 'observed', 'suspected', 'expected' or 'not expected' to affect the performance of various types of soil covers.
- The role of vegetation on cold regions covers including available literature on cold regions evapotranspiration and rooting depths were reviewed.
- The state-of-the-art of computer modelling of cold regions soil covers and related hydrologic processes was reviewed.
- Possible applications of convective cooling in both rock piles and cover systems were examined using a series of bounding calculations.
- The potential for insulating layers to limit freeze-thaw effects on low-permeability barrier layers was examined.
- Ongoing soil cover trials or research programmes in locations that might experience cold regions effects were identified and tabulated.

INAC's next course of action was to lead the development of a guidance document for covers in cold regions. This document not only outlines the current state-of-knowledge of cover design in cold regions, but the expectations of INAC on how a cover design process should be conducted and what information INAC expects to receive during the design process so that an informed decision on the best cover design can be made. In particular, INAC-CSP requires that critical questions in regards to cold region cover systems be addressed: i) what are the key processes that will affect performance of different types of cover systems within a cold regions context; ii) how should the design process incorporate these issues; and iii) what are the risks to long-term performance as a result of these cold regions phenomena. The present paper describes the cover design philosophy that applies to the cover system design in cold regions. The cover design philosophy is part of the technical guidance document.

2 Key attributes of cold regions

In the context of mine waste covers, an appropriate definition of cold regions would include any area where there is a regular occurrence of ground frost sufficient to affect cover performance. The southern limit of significant ground frost in Canada's north extends to about the 40th parallel. Engineers identify this southern limit by a 30 cm depth of frost penetration. However, actual data on frost depth is limited (Andersland and Ladanyi, 2004). Therefore, frost depth is often estimated from the freezing index, which uses only meteorological data to assess the combined duration and magnitude of below-freezing air temperatures during a year (Brown and Kupsch, 1974). The 30 cm frost penetration depth corresponds to a freezing index of 55°C days; this estimate is approximate only as many other factors such as soil mineral and textural composition, snow cover and vegetation can also affect frost depth.

Cold regions typically experience extreme climate, the most obvious of which is prolonged cold air temperatures. Site climate is extremely important to the performance of cover systems, and along with the availability of cover materials, is one of the two key inputs to cover design. In temperate regions, the importance of climate relates predominantly to moisture transfer between the atmosphere and the ground. In cold regions, the importance of climate extends to heat transfer between the atmosphere and the ground. Other cold regions climate factors affecting cover performance include snow cover, surface radiation, convective heat flow, evaporation, and condensation.

In cold regions, there is a distinct link between climate and the ground surface. Extreme climatic conditions result in the ground surface reacting in ways not experienced in other temperate regions of the world. Washburn (1973) stated that where a climate is sufficiently cold it will leave physical evidence of its influence. Common terrain features associated with cold regions include:

- Ice wedges.
- Pingos and palsas.
- Thermokarst.
- Patterned ground
- Boulder fields / pavements.
- Mounds and/or hummocks.
- Mudboils, circles and diapirs.
- Involutions.

MEND 1.61.5a (2009) includes a description of each of the above terrain features. The significance of frozen ground phenomena for cold regions covers will depend on the time scales under consideration.

3 Cover design philosophy for cold regions

3.1 Need for development of site closure objectives and criteria

The key closure objectives for most sites are determined based on the final land-use and revegetation plan for each area of the mine site. All stakeholders including local communities should be consulted to determine the preferred use for the various components of a mine site e.g. open pits, tailings impoundments, waste rock piles, etc. The land-use should take into account the desired land capability of the rehabilitated area and determine whether this requires waste isolation or waste stabilisation to maintain this land-use. If vegetation is desired for a decommissioned waste storage facility, then the climax vegetation community will have a considerable influence on the design and performance of a cover system. The cover system design for a mine waste storage facility must be consistent with the closure objectives for the mine site.

Once stakeholders agree upon the site closure objectives, closure criteria specific to a waste storage facility must then be developed. When determining the performance criteria for a site, the objective is to determine the appropriate level of control e.g. oxygen ingress and/or net percolation, required by the cover system. Key closure criteria include surface and groundwater quality concentration limits for constituents of concern, the design earthquake event for long-term geotechnical stability, acceptable rates of soil erosion, the design storm event for the surface water management system, and desired revegetation outcome/success. Once these criteria have been defined, a cover system and final landform can be designed to ensure the rehabilitated waste storage facility meet the required closure criteria.

3.2 Mine closure planning and progressive reclamation

Although INAC's covers in cold regions guidance document is focussed toward abandoned mines, it is important to discuss two important elements that should be implemented for operational mines: mine closure planning and progressive reclamation.

Mine closure planning is a process that involves determining the site closure objectives, such as final land-use, and determining the processes and steps required to meet those objectives. When closure planning is done prior to closure (or abandonment) of the mine, then the closure objectives can be included in the mine planning. This may include segregation of waste streams, stockpiling topsoil and non-reactive overburden, and, ideally, progressive reclamation.

Progressive reclamation, or reclaiming completed mining landforms during mine operations, is a valuable process because it allows the operator to amortise closure costs over the life of the mine and allows for an iterative process in determining the best reclamation practices. Monitoring the performance of the reclamation while the mine is still operational is much more cost-effective than monitoring post-closure. The results of performance monitoring can then be integrated into the closure plan and modifications made to optimise the design of subsequent reclamation plans.

3.3 Cover design objectives

Several factors influence and often dictate the design objectives of a cover system. The key factors for covers in a cold region include:

- Surface energy balance.
- Surface water balance.
- Geochemical and geotechnical characteristics of the waste material.
- Hydrogeological setting of the waste storage facility.

The ground surface undergoes constant exchanges of mass and energy. In cover design, mass fluxes are largely water and vapour fluxes and are commonly evaluated using a water balance. In cover design for warmer climates, energy balances are not typically considered on their own because energy fluxes are usually only considered pertaining to movement of water vapour through the cover profile. However, for colder climates, energy balances are of greater importance to estimate ground freezing and thawing. The depths of ground freezing and thawing strongly influence the hydrological processes that occur, such as infiltration and redistribution of meltwater (Zhang et al., 2008).

Yamazaki et al. (1998) reported that the daily frost depth in the ground depends much more on the temperature profile inside a snow cover than on soil water content (at least when the latter was more than 0.1) or on vegetation. Solar radiation, thermal radiation, sensible heat flux, latent heat flux including phase change, soil heat flux and advection are key processes for energy exchange between soil covers (land) and atmosphere. These factors vary temporally and spatially, which leads to temporal and spatial variability of a surface energy balance, and hence cover design objectives, in cold regions.

The surface water balance of a soil cover is associated with precipitation, runoff, evapotranspiration, and infiltration. Surface water balance evaluation is crucial for soil cover design because maintaining low infiltration rates can result in low contaminant loading to the environmental receptors. Cold regions generally experience seasonal precipitation with large snowfall in winters. Snowmelt in spring and/or summer may result in high water infiltration into the underlying wastes; therefore, cover design in cold regions should consider surface water balance for extreme climates.

The geochemical and geotechnical characteristics of the waste material could have significant influence on cover design objectives. For example, controlling contaminant release and provision of a growth medium may be the cover design objectives for a reactive waste rock pit, while providing a growth medium could be the main objective for non-reactive oil sands tailings.

The hydrogeological setting of the waste storage facility provides pathways for contaminants released from the waste material to the final environmental receptors. A relatively sealed hydrogeological setting could reduce the risk of the contaminant moving to the environmental receptors, thus benefiting the cover design and design objective.

The objectives of a cover system may vary from site to site but generally include:

1. Dust and erosion control.
2. Chemical stabilisation of mine waste (through control of oxygen or water ingress).
3. Contaminant release control (through control of infiltration).
4. Provision of a growth medium for establishment of sustainable vegetation.

Dust and erosion are minimised through placement of a material layer suitable for growth of vegetation to stabilise the soil. Mulch can also be used to temporarily stabilise the surface, especially before vegetation has become established. Erosion can also be controlled by shaping the landform of the cover surface; for example, hummocks are often used in wet climates to minimise erosion during rainfall events.

The principal mechanism utilised to inhibit oxygen ingress is to utilise the low rate of oxygen diffusion through water. This can be obtained through the development of tension-saturated conditions within a soil cover or the use of a surface pond. In the case of a soil cover, a tension saturated layer of cover material limits the oxygen diffusion rate into the waste to the rate at which oxygen can diffuse through water; in essence, providing a 'water' cover without the requirement for a surface pond.

Limiting the net infiltration of water into the waste is generally achieved by one of three methods. The cover may be constructed of materials with a sufficiently low hydraulic conductivity (a 'barrier') so as to limit downward percolation of rainfall or snowmelt. This water is then stored near the surface of the soil cover or is released as surface runoff and/or interflow. Secondly, infiltrating water is stored within the cover near the ground surface where it can be subsequently released via evapotranspiration. In these 'moisture store-and-release' type covers, the objective is to minimise deep percolation of water by returning all infiltration waters to the atmosphere. A third method of limiting infiltration can be taken advantage of in cold climates where the waste material can be frozen into the permafrost. At freezing temperatures most of the soil water changes to ice and subsequently has a lower hydraulic conductivity. For all three methods of controlling infiltration, the local climate plays a major role in what type of cover is applicable.

The establishment of sustainable vegetation is achieved by placing a layer of soil or other appropriate materials that will support growth of the target plant species groupings. The important factors when designing a vegetative support layer, sometimes referred to as a growth medium layer, are the physical and chemical characteristics of the soil. Particularly, the layer must have sufficient water storage capacity throughout the growing season, and the hydrology of the site must be such that the potential for contaminants to migrate into the vegetative layer is minimised.

The cover design objectives should be site-specific. Site-specific objectives allow the needs of all the stakeholders to be included in the design process from the beginning. With clearly defined objectives, the cover designer has a more defined scope to proceed with the site and material characterisation and the development of the conceptual cover designs. The cover objectives may need to be revised based on field and performance information.

3.4 Utilising attributes of the Canadian North

Historically, many cold region covers have been designed based on experience and technologies developed for temperate regions. It is then hoped that the cover design will not fail over time due to differences in the climatic and geologic setting between the north and south. Where possible, cold region covers should be designed to take advantage of the climatic and geologic setting inherent to the north. Key attributes of the Canadian North pertinent to the design of a mine waste cover system include:

- Low precipitation in the form of spring snow-melt and summer storm events relative to most other parts of Canada.
- High actual evapotranspiration (AET) rates compared to typical rainfall amounts during the summer months due to warm temperatures and long daylight hours.
- Prolonged, cooler temperatures during the winter months which can result in deeper frost penetration.

- Glacial deposits of relatively coarse-textured soils, which are less susceptible to frost action and may be suitable for a capillary break layer.
- High runoff coefficient in the spring when only the upper surface has thawed.
- Surfaces are covered by snow and ice most of the year, thus limiting exposure.

Taking into account the above attributes, where possible, designers should consider incorporating the following elements into a cold region cover design:

1. Divert snow-melt waters to the greatest extent possible by incorporating topographic relief in the final landform design and/or a seasonally frozen layer.
2. Maximise AET rates during the summer months by establishing vigorous vegetation covers. This establishment and subsequent water removal can be enhanced by incorporating organics or fine-textured mineral materials, where available, in the upper cover profile to increase the amount of available soil water for plant and atmospheric demands.
3. Encourage deep freezing of the waste material where possible to minimise percolation of meteoric waters through the waste material.
4. Use compacted coarse-textured materials to achieve relatively low hydraulic conductivity due to the negative effects of frost action on fine-textured materials such as compacted silt/clay or compacted sand-bentonite within the active zone.
5. In tailings covers (saturated waste), address the potential for post-cover construction deformation due to freezing of contaminated water.
6. If required, liners must be installed where they are not subject to freeze-thaw processes.
7. Consider the cost benefit of post-closure sustainability into upfront cover investment in relation to proposed design life.

3.5 Designing for sustainability

Often in the design and construction of a multi-layer earthen cover system, the focus of the design is on the barrier layer. While the importance of the barrier should not be discounted, neither should the importance of the overlying growth medium (Ayres et al., 2004). The growth medium layer is provides the means for establishing vegetation to meet end land goals, as well as to improve cover system performance through evapotranspiration (ET). Establishment of vegetation on growth mediums in the arctic is largely influenced by soil type, local terrain, moisture regime, ecology and climate (Slaughter and Kane, 1979; Gibson et al., 1993). Once vegetation is established ET rates change substantially throughout the year as they are affected by seasonal changes in soil and air temperature, insulation, air humidity, leaf area index and soil moisture (MEND 1.61.5b, 2010). Typically ET increases from May to its peak in July after which it gradually decreases (Vourlitis and Oechel, 1999). Normal daily ET values in these regions range from approximately 0.5–6 mm, with average annual values ranging from approximately 125–475 mm (MEND 1.61.5b, 2010). Although ET rates are largely controlled by external abiotic factors, biotic factors such as plant physiology and community assemblages also result in ET variation across cold regions. McFadden et al. (1998) observed that ET in cold region communities was strongly correlated with vegetation species, cover, and substrate moisture regime. For instance, the authors determined that the highest ET rates were associated with wet tundra sedges and grasses, growing in areas with standing water present for the majority of the growing season at high densities (>90%). Conversely, low daily ET values were associated with dry tundra type communities. While assessing the performance of cover systems in cold regions, it is important to consider the temporal, physiological, and interacting effects of vegetation that act to alter ET rates throughout the year. In addition to facilitating water removal through evapotranspiration, the growth medium layer serves as protection against physical processes, such as wet/dry and freeze/thaw cycling, as well as various chemical and biological processes. An inadequate growth medium layer will not properly protect the barrier layer, leading to possible changes in its performance (INAP, 2003). One of the most common factors leading to failure of multi-layer earthen cover systems is an inadequate thickness of growth medium material over the lower hydraulic conductivity layer (Taylor et al., 2003). One key factor to consider during the design of a multi-layer cover system is the available water holding capacity of the growth medium layer to ensure plant demands for soil water can be satisfied under drier climatic conditions, thus minimising the potential for root penetration and desiccation of the barrier layer. A final consideration for the long-term sustainability of cover system performance in cold regions is reduction of permafrost associated with climate change, more specifically warming in northern latitudes. Melting of permafrost has raised concern in the scientific community; in relation to cold region soil covers, permafrost offers several benefits for cover performance which include impediment of vertical drainage, negatively affecting infiltration rates, and increasing levels of runoff (Carey and Woo, 2001). If permafrost and its associated benefits were to become less prevalent, failure of cover performance would most likely not ensue. In this instance failure is an iterative process and hence should be viewed as a probability curve, which highlights the probability of the cover system being able to 'supply' the appropriate conditions to support the desired vegetation and achieve cover performance objectives (Elshorbagy and Barbour, 2006). A warmer northern climate and associated permafrost melt would most likely result in conditions more suitable for a larger variety of vegetation and/or vegetation that transpires water at a higher rate (taller shrubs and trees). As such, increased soil moisture and available water holding capacity (AWHC) due to permafrost melt could shift the site capability to a wetter system, where another community could occupy the site over another operative edatopic range.

The longevity of a cover design should be evaluated in relation to site-specific physical, chemical, and biological processes that will alter as-built performance and determine long-term performance. Some physical processes include erosion (water and wind), frost heave, frost degradation (thermokarst), slope instability, wet/dry cycles, freeze/thaw cycles, consolidation, extreme climate events, and brushfires. Chemical processes include of osmotic consolidation, dispersion, dissolution, sorption, acidic hydrolysis (chemical weathering), oxidation, salinisation, and mineralogical consolidation. Biological processes include root penetration, burrowing animals, bioturbation, human intervention, bacteriological clogging, vegetation establishment and physiology. It is noted, however, that in many respects the impact of biological and chemical processes specific to a site on long-term cover performance can only be evaluated from a qualitative perspective. In contrast, many of the physical processes affecting long-term performance are quantifiable using state-of-the-art technology, provided that adequate materials characterisation data are available. Recent reviews based on 10 to 15 years of cover performance data indicate that covers may limit, but do not stop, infiltration and sulphide oxidation (Wilson, 2008; Wilson et al., 2003; Taylor et al., 2003). However, the achieved reduction in oxidation (and attendant acid rock drainage and metal leaching) may be sufficient to meet design goals and at a minimum would reduce water treatment requirements.

3.6 Importance of final landform design

Final landform design is an important consideration for designing cover systems for waste storage facilities located in cold regions. Poor surface water management and landform instability are common factors leading to failure of cover systems around the world (MEND 2.21.4, 2004). The primary reason for this is a design approach that attempts to build engineered structures to oppose natural processes rather than developing engineered systems based on natural analogues that integrate rapidly with the surrounding hydrologic and ecosystems following implementation (Ayres et al., 2006). Careful consideration must be given to the planned final landform for a waste storage facility to ensure that performance of a given cover system can be sustainable over the long-term.

Landform evolution modelling has become increasingly common in the design of mine closure landscapes in moderate climates. These models essentially link hydrological response of the landform to precipitation (rainfall) to an estimate of erosion and sediment loss over a three-dimensional landscape. The potential application of these models to cold regions is not well understood as the primary runoff events would be linked to snowmelt runoff and the thickness of the active layer rather than precipitation events. In addition, these models have not been calibrated to any existing cold region sites, natural or engineered.

Final landform design is particularly important in terms of cover system design for waste storage facilities located in cold regions. Often, the methods to achieve a stable landform in a more temperate climate have more complex consequences in cold regions. For example, it would be ideal to limit snowpack development on a waste storage facility from an environmental loading and erosion perspective; however, this results in the cover profile being more susceptible to freeze/thaw cycling, which could have detrimental impacts on long-term performance. Increasing the thickness of snowpack through reduction of wind drifting will reduce the thickness and thus construction cost of a growth medium layer designed to prevent frost penetration into an underlying barrier layer. However, this creates a challenge in dealing with large spring melt runoff.

3.7 Assessment period and design life

Cover design practitioners, through consultation with INAC and regulatory agencies, need to determine an appropriate period for assessing post-closure performance of various cover design alternatives. Philosophically, remediation of mine waste storage facility should generate a walk-away solution, with an infinite lifespan. However, as with all engineering, anything that is designed is also subject to failure and therefore has a fixed lifespan. Cold regions, in general, have a lower population density and are more remote than warmer climates. Therefore, the ability to perform long-term monitoring is decreased and the ability to provide mitigating measures, should they be necessary, is also decreased and more expensive. For this reason, the assessment period for a cold region site should be longer compared to that typically used for sites in temperate regions.

The concepts for the assessment period and design life are different. The design life of a product or structure is the period of time during which the item is expected by its designers to work within its specified parameters; in other words, the life expectancy of the item. While the assessment period is a timeframe during which the designed product or structure is evaluated with extreme events and no catastrophic failure is expected to happen. In general the design life is shorter than the assessment period. For example, a cover system may be designed for 100 years but assessed for 1,000 years; in other words, the cover system is expected to maintain performance for 100 years and will not undergo catastrophic failure (high hazard) for 1,000 years. The purpose of the assessment period is to evaluate the necessary maintenance on the basis of the assessment period for the probability of catastrophic failures and/or other high hazards. Funds need to be set aside to repair the product for the duration of the assessment period if necessary.

The selection of the assessment period and design life depends on the regulatory requirement, cover design objectives, closure panning, and cost. It should be noted that the cost should be evaluated for the whole assessment period.

4 Summary

Compared to soil cover design in temperate climate, the soil cover design in cold regions is just in its very beginning. Although some knowledge and experience obtained from the cover design and cover performance in the temperate sites may be applicable in cold regions, special features such as extreme climate and relative coarse-textured material in cold regions require specially developed technical guidance for cold region cover design. The cover design philosophy presented in the paper describes the main aspects for designing soil covers in cold regions. Application of the cover design philosophy should be incorporated in the site-specific settings. The development of the technical guidance document is intended to be a resource for guiding cover designers to consider all possible solutions. From INAC’s perspective, the lowest cost option for a cold region cover may not be the best alternative when all issues surrounding long-term performance and liability are considered.

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References

Andersland, O.B. and Ladanyi, B. (2004) Frozen ground engineering, John Wiley & Sons, Inc., Hoboken, New Jersey, 363 p.

Ayres, B., Dobchuk, B., Christensen, D., O’Kane, M. and Fawcett, M. (2006) Incorporation of natural slope features into the design of final landforms for waste rock stockpiles, in Proceedings 7th International Conference for Acid Rock Drainage, 26–30 March, St. Louis, MO, USA, pp. 59–75.

Ayres, B.K., O’Kane, M. and Barbour, S.L. (2004) Issues for consideration when designing a growth medium layer for a reactive mine waste cover system, Proceedings 11th International Conference on Tailings and Mine Waste, 10–13 October, Vail, Colorado.

Brown, R.J.E. and Kupsch, W.O. (1974) Permafrost Terminology, Natural Research Council of Canada, Ottawa, Ontario, 62 p.

Carey, S.K. and Woo, M.K. (2001) Spatial variability of hillslope water balance, Wolf Creek basin, subarctic Yukon, Hydrological Processes, Vol. 15, pp. 3113–3132.

Elshorbagy, A. and Barbour, S.L. (2006) Risk and uncertainty-based assessment of the hydrologic performance of reconstructed watersheds, Paper submitted to ASCE Journal of Geotechnical and Geoenvironmental Engineering (under review).

Gibson, J.J., Edwards, T.W.D. and Prowse, T.D. (1993) Runoff generation in a high boreal wetland in northern Canada, Nordic Hydrology, Vol. 24, pp. 213–224.

INAP (2003) International Network for Acid Prevention Evaluation of the long-term performance of dry cover systems, final report, Prepared by O'Kane Consultants Inc., Report No. 684–02, March 2003.

McFadden, J.P., Chapin III, F.S. and Hollinger, D.Y. (1998) Subgrid-scale variability in the surface energy balance of arctic tundra, Journal of Geophysical Research, Vol. 103(22), pp. 947–961.

MEND 1.61.5a (2009) Mine waste covers in cold regions, Mine Environmental Neutral Drainage (MEND) Programme, March 2009.

MEND 1.61.5b (2010) Cold regions cover research – Phase 2, Mine Environmental Neutral Drainage (MEND) Programme, November 2010.

MEND 2.21.4 (2004) Design, construction and performance monitoring of cover systems for waste rock and tailings, Mine Environmental Neutral Drainage (MEND) Programme, July 2004.

Slaughter, C.W. and Kane, D.L. (1979) Hydrologic role of shallow organic soils in cold climates, Proceedings Canadian Hydrology Symposium 79–Cold Climate Hydrology, National Research Counsil of Canada, Ottawa, pp. 380–389.

Taylor, G., Spain, A., Nefiodovas, A., Timms, G., Kuznetsov, V. and Bennett, J. (2003) Determination of the reasons for deterioration of the Rum Jungle waste rock cover, Australian Centre for Mining Environmental Research, Brisbane.

Vourlitis, G.L. and Oechel, W.C. (1999) Eddy covariance measurements of CO2 and energy fluxes of an Alaskan tussock tundra ecosystem, Ecology, Vol. 80 (2), pp. 686–701.

Washburn, A.L. (1973) Periglacial processes and environments, Edward Arnold Ltd., London, England, 320 p.

Wilson, G.W. (2008) Why are we still struggling with ARD? Geotechnical News, BiTech Publishers Ltd., Vancouver, Canada, June 2008, pp. 51–56.

Wilson, G.W., Williams, D.J. and Rykaart, E.M. (2003) The integrity of cover systems–An update, Proceedings 6th International Conference for Acid Rock Drainage, 12–18 July, Cairns, North Queensland, Australia, pp. 283–291.

Yamazaki, T., Nishida, A. and Kondo, J. (1998) Seasonal frost depth of grounds with the bare surface, snow cover and vegetation, Journal of Japanese Society of Snow and Ice, Vol. 60, pp. 213–224 (in Japanese with English summary).

Zhang, Y., Carey, S.K. and Quinton, W.L. (2008) Evaluation of the algorithms and parameterisations for ground thawing and freezing simulation in permafrost regions, Journal of Geophysical Research, Vol. 113, D17116, doi: 10.1029/2007JD009343.