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Risk-based soil remediation guidelines in coal mine closure

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Abstract

The closure of coal mines and associated processing facilities presents many challenges, including the management of contaminant chemicals that may have been released over a potentially long and varied history of industrial activity at a site. However, the high carbon content of coal waste material that may be present at some facilities can actually facilitate site closure by decreasing the mobility of organic contaminants. The Coleman Collieries facility, located in the Municipality of Crowsnest Pass in south west Alberta, Canada operated for approximately 80 years as a coal mining and processing facility. During that time, coal waste and unmarketable coal fines from settling ponds were placed over much of the facility to a depth of 3–4 m. The Province of Alberta, like many jurisdictions, uses risk-based soil guidelines as one of the criteria in assessing whether land, such as a former mine facility, is suitable for a proposed post-closure use. Assessment of the Coleman facility found a range of contaminants exceeding Alberta's default soil guidelines including benzene, toluene, ethylbenzene, and xylenes (BTEX) and other hydrocarbon compounds and fractions. Alberta's soil guidelines were developed to be protective of a range of exposure pathways including vapour migration into indoor air spaces and groundwater transport to potential aquifers or surface water bodies. However, these guidelines were developed based on the expected mobility of organic compounds in typical subsoils with low organic carbon contents. Site-specific soil guidelines were developed for the Coleman facility which took into account the much higher carbon content of soils at this facility, to more accurately determine the remedial actions required for site closure.

1 Introduction

The closure of coal mines and associated processing facilities presents many challenges, including the management of contaminant chemicals that may have been released over a potentially long and varied history of industrial activity at a site. Conventionally, contaminant chemicals in soil or water at a site are assessed against a series of generic limiting contaminant concentrations, referred to as remediation guidelines, criteria, or standards by various regulatory agencies. In this paper, such limiting concentrations will be referred to as remediation guidelines, consistent with the usage of Alberta Environment (AENV), the applicable regulatory agency. Increasingly, regulatory agencies are becoming aware that appropriate remediation guidelines can vary significantly based on a range of site-specific factors that cannot reasonably be incorporated in a generic table of guidelines. Accordingly, many regulatory agencies are now receptive to, or actively encouraging using risk-based approaches to calculate site-specific remediation guidelines for individual sites.

This paper uses the former Coleman Collieries facility ("the facility"), located in the Municipality of Crowsnest Pass in southwest Alberta, Canada as a case study to illustrate how site-specific soil remediation guidelines for hydrocarbons were calculated to take into account the carbon content of soils at this facility, to more accurately determine the remedial actions required for site closure.

2 Background

2.1 Facility operational history

The facility was operational for 80 years, from 1903 to 1983. The principal activities associated with the facility included:

- Coal mining.
- Coal processing.
- Coke production.
- Briquette manufacturing.

Originally, coal was produced from underground mines located north and south of the facility. Rock debris from these mining operations was tipped into several gully features on the south side of the river, while coal was transported for processing in the northern part of the facility. Three processing plants are thought to have been present on the facility. Currently, only one plant remains. The existing processing plant was constructed in the late 1960s. Coal processing at the facility consisted primarily of crushing the raw coal, and using a flotation process to separate the marketable pieces of coal from the lower grade material. Marketable coal was shipped from the Facility by rail. The unmarketable fines from the processing plant were piped to settling ponds and excess water was allowed to drain. Coal fines, assumed to originate from former settling ponds, together with waste rock and other coal-related material including ash, now cover much of the Facility to a depth of 3 to 4 m. These materials are collectively referred to in this paper as “fill materials”.

Coke was produced in a series of beehive ovens at the facility, in which coal was heated and the ingress of air restricted. Hot coke was raked out of the ovens and quenched with water. Coke production ceased in the 1950s and some of the ovens were dismantled. Coke was shipped from the facility by rail.

Briquettes were manufactured on the facility from 1952 to 1956. The briquetting plant was located just west of the Locomotive Shed at the north end of the second (now dismantled) preparation plant. The binder for the briquettes was bulk asphalt that was stored in two of the three above-ground storage tanks located just south of the Locomotive Shed. There was no diluent for the asphalt, however, diesel was commonly used to clean asphalt off equipment associated with the briquetting operations.

2.2 Physical setting

The facility is located immediately south of the town of Coleman, and occupies an area of approximately 140 ha along the north and south sides of the Crowsnest River.

The current ground surface of the facility north of the river is relatively flat, however, as noted previously, the surface elevation of much of this part of the facility has been raised by 3 to 4 m from original levels due to the addition of fill materials. South of the river there is a narrow flood plain, and then the ground rises rapidly to the southern boundary of the facility and beyond. Several pre-existing valley/gulley features on this hillside have been filled with rock tailings from mining operations.

The Crowsnest River flows from west to east across the facility, and is currently located at the southern edge of the floodplain. Three local streams/drainages are present on the facility north of the Crowsnest River. McGillivray Creek is close to the western margin of the facility, while Nez Pierce Creek forms part of the eastern boundary of the facility. The international ditch starts from a large spring just west of the loadout area within the facility, joins the intermittent creek that follows a former channel of McGillivray Creek, and flows to the Crowsnest River over the central part of the facility, passing through two culverts.

The regional setting of the facility, hills and mountains to the north and south, and a river running east–west through the facility, implies that the hills and mountains will feed groundwater to the valley. Thick alluvial gravels (up to 7 m) in the floodplain of the Crowsnest River can accommodate significant groundwater flow. Creeks crossing the floodplain may lose a substantial part of their flow to the alluvial gravels. Thus the major contribution to the flow in the Crowsnest River through the facility is via groundwater, rather than surface discharge.

2.3 Redevelopment goals

The facility has been inactive for some time and is located in close proximity to a residential and commercial area. Both the facility owners and the Municipality of Crowsnest Pass would like to see the facility returned to productive use consistent with its location. Assessment and appropriate remediation of contaminant chemicals were undertaken to ensure the protection of human health and environmental health under a future residential land use.

2.4 Regulatory framework

The facility is currently subject to an Approval under the Alberta *Environmental Protection and Enhancement Act*. Decommissioning and reclamation of the facility is required for closure of the Approval. Alberta Environment (AENV, 2010a, 2010b) has a framework for the management of contaminated sites which governs the steps required for site closure. This framework allows sites to be assessed relative to the generic "Tier 1" remediation guidelines for the appropriate land use and soil type. The framework also allows site-specific "Tier 2" remediation guidelines to be generated that take account of the properties of a site that may differ from the properties assumed in the calculation of the Tier 1 guidelines.

This paper illustrates the process and some of the challenges encountered in the calculation of Tier 2 guidelines for hydrocarbons at the facility that focused on the higher organic carbon content of fill materials at the facility relative to the organic carbon content that was assumed in the calculation of the AENV Tier 1 guidelines.

Tier 1 soil remediation guidelines for residential land use and coarse soil that would be applicable to the post closure use of the facility are summarised in Table 1.

Table 1 Applicable AENV Tier 1 soil remediation guidelines (mg/kg)

	Overall Tier 1 Guideline	Human Direct Contact	Human Inhalation	DUA	Eco-contact	FAL	Management Limit
Benzene	0.073	78	0.073	0.078	31	1.6	-
Toluene	0.49	20,000	95	0.95	75	0.49	-
Ethylbenzene	0.21	8,500	44	0.21	55	540	-
Xylenes	12	140,000	12	28	95	250	-
F1	24	12,000	24	2,200	210	1,300	700
F2	130	6,800	130	2,900	150	520	1,000

Notes: DUA is the guideline for the protection of domestic use aquifer pathway. Eco-contact is the guideline for the ecological direct contact exposure pathway. FAL is the guideline for the protection of freshwater aquatic life pathway.

2.5 Distribution of chemicals of concern

Various phases of environmental site investigation were undertaken at the facility to characterise the nature and distribution of contaminant chemicals in soil at the facility. Chemicals of potential concern identified for the facility included metals and hydrocarbon compounds, including polycyclic aromatic hydrocarbons (PAHs). Metal issues were managed using a combination of remediation, risk management, and comparison with background concentrations. Tier 2 guidelines were calculated for hydrocarbon compounds accounting for the higher organic carbon content of the fill materials.

Two distinct patterns of contaminant distribution were found for hydrocarbon compounds. A release of hydrocarbons in the vicinity of the former locomotive shed had resulted in a well defined area with elevated levels of heavy hydrocarbons. This area was remediated by conventional means (excavation and removal to landfill). Hydrocarbon compounds were also detected in samples from around the facility in an entirely different pattern, in which most samples had non-detectable or very low concentrations of some hydrocarbon compounds, but a small number of individual samples showing slightly higher concentrations (some above Tier 1 guidelines) were distributed in a seemingly random pattern across the facility.

Using conventional remediation techniques to address this scattered distribution of minor hydrocarbon exceedances through such a large volume of mostly uncontaminated material would be impractical, and accordingly the approach of developing Tier 2 guidelines was adopted. For completeness, Tier 2 guideline values were developed for all potentially relevant hydrocarbon compounds, including benzene, toluene, ethylbenzene and xylenes (BTEX), F1, F2, and F3 petroleum hydrocarbon fractions and all 16 of the polycyclic aromatic hydrocarbon compounds included in AENV (2010a). However, in the interest of clarity and brevity, this paper focuses only on the Tier 2 guidelines calculated for BTEX, F1, and F2.

3 Development of Tier 2 guidelines

Tier 2 guidelines were developed based on principles provided in AENV (2010b) to account for the higher organic carbon content of fill materials relative to the default value of 0.5% assumed in the calculation of the Tier 1 guidelines. Each of the following exposure pathways is considered in turn in the sections that follow.

- Human indoor vapour inhalation.
- Ecological (plants and soil invertebrates) direct contact with soil.
- Groundwater mediated pathways.

3.1 Carbon content of fill materials

The “fraction of organic carbon” was determined analytically for a total of 18 samples of the fill materials from locations across the facility (Table 2). The fraction of organic carbon was calculated by subtracting the inorganic carbon concentration from the total carbon concentration in a sample. The inorganic carbon was determined from the mass loss (of CO_2) when the soil was treated with acid. The total carbon content was determined by combustion in a quartz tube at 900ºC in the presence of oxygen with CO_2 detection and quantification by thermal conductivity. Note that fraction of organic carbon (f_{oc}) calculated in this way includes true organic carbon and elemental carbon i.e. coal, but not inorganic carbon (i.e. carbonate, bicarbonate). The arithmetic mean of the f_{oc} values for all samples analysed was 44%.

The distribution of f_{oc} within the fill materials is heterogeneous, as indicated by the values in Table 2. However, the majority of samples (15 out of 18, or 83%) indicate a relatively high f_{oc} of 28% or higher. The relevance of f_{oc} is the retardation effect that the carbon will have on the transport of organic contaminants in the subsurface. While heterogeneity in f_{oc} may affect subsurface contaminant transport at small scales, the larger the scale considered, the closer contaminant transport can be estimated based on the mean value of f_{oc}.

As noted in the following sections, uncertainty factors were applied to the mean measured value of f_{oc} to allow for i) any residual uncertainty associated with the heterogeneity of f_{oc}, and ii) any differences in the way that this particular form of carbon interacts with organic contaminants relative to typical soil organic carbon.

3.2 Vapour inhalation

AENV (2010a) calculated Tier 1 soil remediation guidelines for the indoor air vapour inhalation exposure pathway based on a set of assumed default parameters which included a value of 0.5% for the fraction of organic carbon in soil (f_{oc}). This value is typical and appropriate for mineral subsoils in Alberta. However, based on the data in Table 2, the f_{oc} of fill materials at the facility is significantly greater than the Tier 1 value assumed. f_{oc} has a direct effect on the partitioning of hydrocarbon compounds between soil, soil moisture and soil vapour phases. Higher f_{oc} results in more of the hydrocarbon being sorbed to soil, and less being available in the vapour phase. Accordingly, Tier 2 guidelines were calculated for hydrocarbon compounds taking into account the high carbon content of fill materials.

However, it was noted that the carbon in fill materials is mostly elemental carbon i.e. coal, and may behave differently from the soil organic carbon present in normal mineral soils. Accordingly, following discussions with AENV, it was decided to apply an uncertainty factor of 2 to the mean measured f_{oc}, and use an assumed value of 22% for the “effective f_{oc}” of the fill materials. Further discussions with AENV indicated that Tier 2 vapour inhalation guidelines could be calculated using f_{oc} of 22%; however, soil vapour monitoring would be required in this case to confirm that the model was still valid with such a high value of f_{oc}. An alternative option of using a higher uncertainty factor and no vapour monitoring was eventually adopted for expediency, and Tier 2 guideline values were calculated based on a f_{oc} of 6%. Calculated values are included in Table 3.

Table 2 Fraction of organic carbon (f_{oc}) content of fill materials

Location	Description	Depth Sampled	f_{oc} (%)
7	Ponds	4.0–4.5 m	55.3
7	Ponds	5.5 m	57.3
8	Ponds	0.6–1.0 m	64.9
8	Ponds	2.3–2.6 m	50.6
8	Ponds	3.2–3.6m	50.6
17	Substation	0.6–1.0 m	12.4
22	Wash house	0.3–0.6 m	41.6
36	Preparation plant	0.3–0.6 m	39.1
36	Preparation plant	1–1.5 m	50.8
62	Locomotive shed	1.4–1.8 m	49.1
63	Ponds	0–2.6 m	47.6
100	Preparation plant #2	0.6–1.0 m	52.2
104	West end	1.0–2.0 m	1.7
105	West end	0.3–0.6 m	30.6
106	West end	0.3–0.6 m	28.4
GT–1	Spoil	3.5 m	44.9
GT–4	Spoil	2.0 m	59.4
GT–5	Spoil	3.5 m	9.7
Mean f_{oc} for fill materials		44	

3.3 Ecological direct contact

The toxicity tests on which the current AENV (2010a) ecological contact soil quality guidelines for BTEX and PHC fractions were based used a soil with a carbon content of 6.48% (ESG, 2003). Site-specific Tier 2 guidelines for BTEX and PHC fractions were calculated to take into account the higher carbon content of fill materials at the facility.

Non-polar compounds such as hydrocarbons tend to sorb strongly to carbon. The equilibrium between a non-polar compound sorbed to carbon and dissolved in soil pore water is given by:

$$C_W = \frac{C_S}{K_{oc} f_{oc}} \tag{1}$$

where:

Cw	=	concentration of compound in pore water (mg/L).
Cs	=	concentration of compound sorbed to soil organic carbon (mg/kg).
Koc	=	organic carbon water partition coefficient (L/kg).
f_{oc}	=	fraction of organic carbon (-).

Thus, to a first approximation, we expect the concentration of a non-polar compound in pore water to be inversely proportional to f_{oc}. As noted previously, the effective f_{oc} for fill materials is assumed to be 22%.

Van Gestel et al. (1991) and Van Gestel and Ma (1988, 1990) have shown that the toxicity of chlorophenols, dichloroaniline, and chlorobenzenes for earthworms in soils differing in organic matter content varies with the changing f_{oc}, but is almost the same when expressed in terms of pore water concentration. Hulzebos et al. (1993) came to a similar conclusion in a study on the toxicity of a wide variety of compounds to lettuce, both in soil and in nutrient solution. Accordingly, the ecological contact soil quality guideline can be adjusted for the high carbon content of the facility soils by multiplying by the carbon content of the soil and dividing by the carbon content of the soil in which the toxicity test was conducted, as follows:

$$\text{Tier 2 SRG}_{eco} = \frac{\text{Tier 1 SRG}_{eco} \times f_{oc}(Fill\ Soil)}{f_{oc}(Test\ Soil)} \tag{2}$$

where:

Tier 2 SRGeco = Tier 2 soil remediation guideline for the eco-contact pathway (mg/kg).

Tier 1 SRGeco = Tier 1 soil remediation guideline for the eco-contact pathway (mg/kg).

f_{oc} (Fill Materials) = Fraction of organic carbon in fill materials (22%).

f_{oc} (Test Soil) = Fraction of organic carbon in test soil (6.48%).

Tier 2 ecological soil contact guidelines are summarised in Table 3.

3.4 Groundwater mediated pathways

Groundwater mediated pathways include the protection of domestic use aquifer (DUA) and protection of freshwater aquatic life (FAL) pathways. Guidelines for these exposure pathways protect against mobile contaminants leaching from soil into shallow groundwater and subsequently being transported to either a domestic use aquifer or to a surface water body where humans, freshwater aquatic life or other receptors could become exposed. Tier 2 guidelines were calculated for these exposure pathways using a f_{oc} of 22%. The calculated Tier 2 guidelines indicated that these exposure pathways were not expected to be of concern. This conclusion was supported by chemical analysis indicating that hydrocarbon compounds were either not detected or were present at trace levels in shallow groundwater. Accordingly, these exposure pathways were considered to be assessed appropriately by direct groundwater monitoring, as indicated by the abbreviation "GWM" (for groundwater monitoring) in Table 3.

4 Results

Tier 2 guidelines calculated for fill materials at the facility are summarised in Table 3. Note that Tier 1 guidelines are applicable to natural soils which underlie the fill materials, and have an organic carbon content consistent with the default value of 0.5%. The overall Tier 2 guideline is the lowest of the guidelines for any of the exposure pathways.

Table 3 Site-specific Tier 2 soil remediation guidelines for fill materials at the facility (mg/kg)

	Overall Tier 2 Guideline	Human Direct Contact	Human Inhalation	DUA	Eco-contact	FAL	Management Limit
Benzene	0.72	78	0.72	GWM	110	GWM	-
Toluene	250	20,000	1,100	GWM	250	GWM	-
Ethylbenzene	190	8,500	500	GWM	190	GWM	-
Xylenes	140	140,000	140	GWM	320	GWM	-
F1	260	12,000	260	GWM	710	GWM	700
F2	510	6,800	1,500	GWM	510	GWM	1,000

Notes: DUA is the guideline for the protection of domestic use aquifer pathway. Eco-contact is the guideline for the ecological direct contact exposure pathway. FAL is the guideline for the protection of freshwater aquatic life pathway. Mgmt. Limit is the management limit. GWM –managed by direct monitoring of shallow groundwater, rather than a soil guideline.

5 Conclusions and current status

The scattered and diffuse nature of the distribution of hydrocarbons in fill materials made conventional remediation impractical over much of the area of the facility. Tier 2 guidelines were calculated that took into account the high organic carbon content of fill materials at the facility relative to the default value of 0.5% assumed in the calculation of the AENV Tier 1 guidelines. Using the Tier 2 guidelines to screen hydrocarbon contaminant issues at the facility allowed remedial efforts to be concentrated on defined areas of known hydrocarbon releases, and demonstrated that the scattered and diffuse occurrences of hydrocarbons would not result in risk to human health or the environment under a future residential land use.

The Tier 2 guidelines for the facility have been accepted by AENV, and the final stage of facility decommissioning and closure is currently underway and expected to be completed by the end of 2011.

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