Journal of Environmental Management 231 (2019) 467–482

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Modelling of vapour intrusion into a building impacted by a fuel spill in Antarctica

R.S. McWatters[a,*], R.K. Rowe[b], D. Wilkins[a], T. Spedding[a], G. Hince[a], J. Richardson[a], I. Snape[a]

[a] *Antarctic Conservation and Management, Australian Antarctic Division, Kingston, Tasmania, Australia*
[b] *Geoengineering Centre at Queen's-RMC, Queen's University, Kingston, Ontario, Canada*

ARTICLE INFO

Keywords:
Cold regions
Vapour barrier
Indoor air
Remediation
Soil reuse guidelines
Biopile

ABSTRACT

A new vapour intrusion contaminant transport model was designed specifically to allow an assessment of the impact of a hydrocarbon fuel spill on air quality in cold region buildings. The model is applied to a recent situation in Antarctica, where a diesel spill impacted the construction of a new building. For the first time, this model allows consideration of the diffusive resistance of different vapour barrier to the transport of hydrocarbons into the building and an assessment of the effectiveness of different products. Site specific indoor air criteria are derived. Five scenarios are modelled at field temperatures: (1) build on current contaminated site; (2) excavate contaminated soil, backfill with clean soil and assess impact of residual contamination; (3) excavate and backfill with remediated (biopile) soil; (4) backfill with remediated soil and assess impact of residual contamination; (5) backfill with remediated soil and assess impact of a potential future fuel spill. Two different vapour barriers, a co-extruded ethylene vinyl alcohol (EVOH) geomembrane (VB1) and a linear low-density (LLDPE) geomembrane (VB2), are investigated for each scenario and compared to a base case with no vapour barrier, providing quantifiable evidence of the benefit of installing an engineered vapour barrier Contaminant concentrations were below regulatory limits for Scenarios (2–5) with VB1 and air exchange in the building. For all scenarios, the EVOH geomembrane (VB1) was consistently superior at reducing vapour transport into the building indoor air space over the LLDPE geomembrane (VB2) and no vapour barrier. The risk mitigation measures developed for this contaminated Antarctic site may be relevant for other buildings in cold regions.

1. Introduction

In winter 2015, a supply line leaked 4000 L of Special Antarctic Blend (SAB) diesel fuel at Casey Station, Antarctica (66.2818°S, 110.5235°E). Snow cover had buried the site and concealed the extent of the fuel spill for more than 3 months. The full extent of the spill, contaminated soil, and contaminated groundwater was not fully appreciated until construction of the foundation of the Casey Utility Building (hereafter shortened to CUB) at the start of the Antarctic summer. Initial observations included light non-aqueous phase liquid (LNAPL) on the shallow groundwater and soil staining (Fig. 1). Subsequent detailed investigations found fuel in soil at depths 0–1.2 m below the ground surface over half the 365 m^2 building area (Fig. 2). During summer, thawing soil significantly increased the groundwater and LNAPL within the building's concrete perimeter foundation (Fig. 3). The building area is downhill from a powerhouse, associated fuel storage tank, and fuel transfer lines (Fig. 3) where there had been two previous recorded spills and thus potential for a future spill. Soils in cold climates often have very little natural attenuation capacity, and hence the plume could easily migrate further and persist longer than it would in warmer environments (Ping et al., 2015; Snape et al., 2005, 2006; 2008; Mohn and Stewart, 2000).

Fuel within the subsoil was a potential risk to human health, as shallow LNAPL significantly increases the risk of contaminant vapour intrusion into buildings (Hers et al., 2014). Building construction was suspended while a risk assessment was conducted to consider the potential impacts on the structure and the long-term health of workers in the (future) building. Following the USEPA technical guidance on response actions to address vapour intrusion, the assessment included the following: (i) undertake contaminant transport modelling to assesses if the indoor air poses an unacceptable human health risk; (ii) consider remediation to reduce and/or eliminate the subsurface vapour source (iii) consider engineering exposure controls (e.g., contaminant vapour barrier, building air exchange) to reduce vapour intrusion and hence vapour concentration; and (iv) monitor air quality and verification of the performance and effectiveness of remediation activities and the

---

* Corresponding author.
E-mail address: rebecca.mcwatters@aad.gov.au (R.S. McWatters).

https://doi.org/10.1016/j.jenvman.2018.07.092
Received 28 September 2017; Received in revised form 25 July 2018; Accepted 26 July 2018
0301-4797/

Fig. 1. Southern view of site before the summer melt (early December 2015). SAB in water and pure phase SAB was upwelling into the building site. An interception barrier was placed up gradient of the building site to prevent more fuel ingress into building footprint.

engineering exposure controls (USEPA, 2015).

Hydrocarbon vapours arise from three sources at the CUB site: (i) free phase fuel (LNAPL), (ii) contaminated ground/surface water, and (iii) contaminated soil. Transport pathways for fuel vapour are shown in the conceptual site model (Fig. 4). Vapour migration is facilitated through permeable bedrock (in the matrix or fractures), permeable building materials (e.g., granular materials, unsaturated soils, concrete), and cracks/voids in the building design (Yao et al., 2013). The CUB, like other buildings designed for the Australian Antarctic stations, was designed with a foundation insulation system to keep the soil below the building frozen. If the soil was initially saturated with water and then permanently frozen, this frozen monolith would act as the primary barrier to inward migration of residual hydrocarbons (groundwater, vapour). If the soil was unsaturated, which is common at Casey Station, the frozen ground would be a poor barrier to contaminant vapours. Furthermore, fuel is known to increase a soil's hydrophobicity, decrease the soil freezing temperature, and increase the depth to permafrost (Aislabie et al., 2004). Vapours can also travel through discontinuous permafrost (e.g., ice formation in the active soil layer can create fissures through which contaminants can escape; Barnes and Biggar, 2008). Therefore, both soil temperature and hydration are important in minimising vapour intrusion into a building. A new vapour intrusion model was needed that would include parameters for the soil conditions specific to this Antarctic environment.

Vapours travel by advection from a sub-surface source into an overlying building; driven by differences in pressure, temperature and moisture between the indoor and outdoor air (Hers et al., 2014; McAlary et al., 2011). Vapours also travel by diffusion; driven by concentration differences and influenced by temperature. Transport can be more pronounced in cold regions due to larger differences between these parameters for indoor and outdoor air (USEPA, 2008). Transport pathways related to vapour intrusion have been widely studied (Yao et al., 2013; Provoost et al., 2009, 2010; Johnson and Ettinger, 1991; Fitzpatrick and Fitzgerald, 1996, 2002; DeVaull et al., 2002; Johnson, 2005; McAlary et al., 2011). However, there has been less research into vapour intrusion in cold climates, where snow cover, cold exterior temperatures and warm interior building temperatures influence soil vapour migration (Hers et al., 2014). Antarctic buildings are often slightly positively pressurised, preventing cold air and blizzard driven snow from entering the buildings. They are also tightly sealed, meaning air and potential contaminants can only exit through an air exchange system. For these reasons, a cold region, site-specific vapour intrusion model was required to investigate if the indoor air would pose an unacceptable human health risk and whether excavation of the contaminated soil was required to eliminate the subsurface vapour source.

Engineering exposure controls were also considered for this site. These included vapour barriers or geomembranes (i.e., continuous sheets of plastic). Historically, vapour barriers were solely used as a moisture barrier in the exterior or foundation of buildings (USEPA, 2008). Recently, improved barrier materials have been used to impede hydrocarbon contaminant migration, thus minimising or retarding vapour intrusion (Jones and Rowe, 2016). If appropriately designed and properly installed and welded (with negligible holes), vapour barriers can minimise advective transport of contaminants, leaving diffusion as the dominant transport mechanism (Rowe et al., 2004). Therefore, in designing a robust barrier system, it is necessary to know the diffusive properties of the barrier, which are specific to polymer type, thickness, temperature, and contaminant type. Different vapour barriers will perform differently, thus researchers have been studying the diffusive properties of many geomembranes used as vapour barriers (Jones and

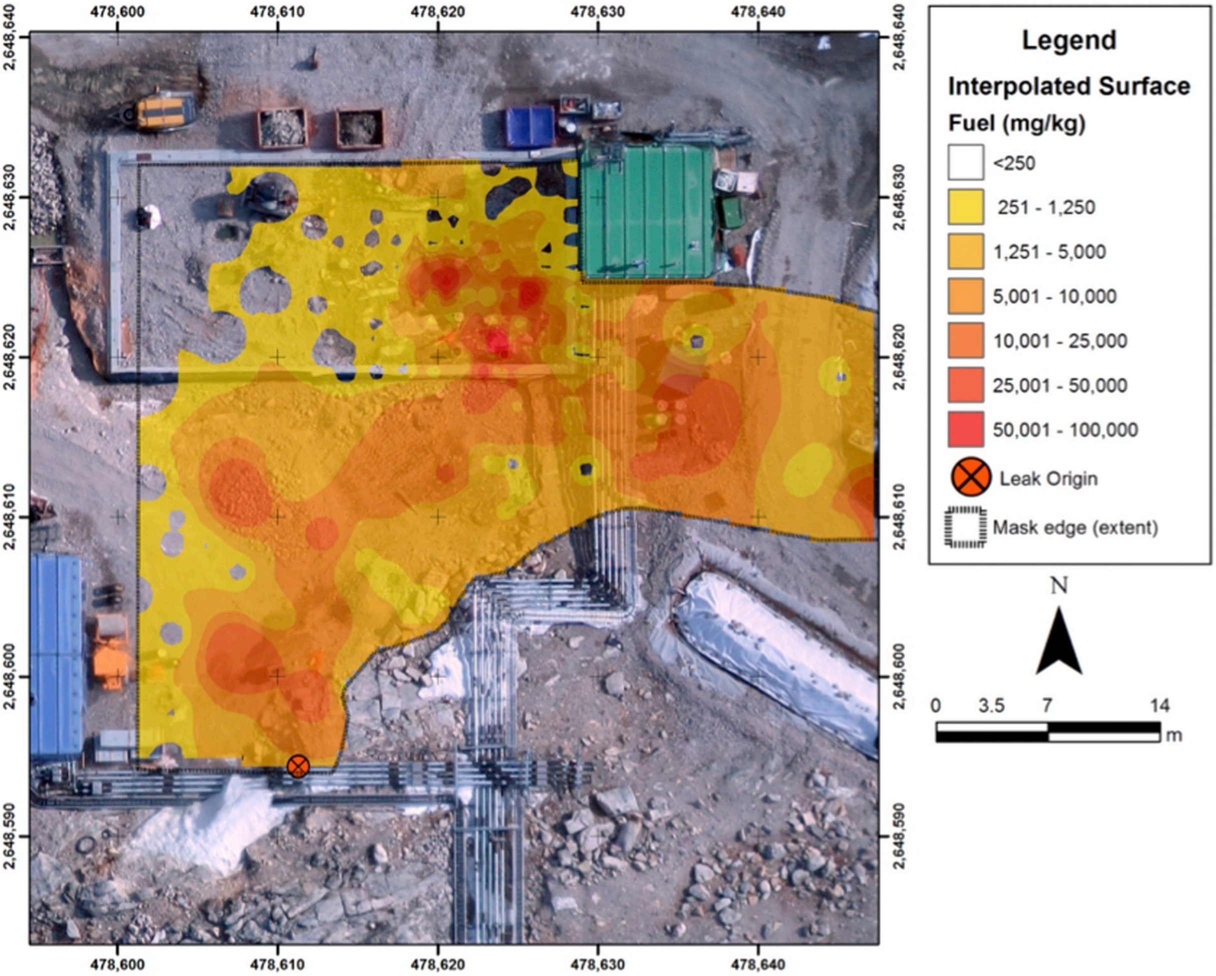

Fig. 2. Background orthophoto mosaic showing the flange (leak origin), Casey Utility Building foundation (rectangular concrete perimeter beams), and existing waste water treatment building (green roof). The colours show an interpolated (inverse distance weighted) surface model of the fuel spill, generated from TPH concentrations derived from soil samples collected at depths up to 100 cm below ground surface during the initial site assessment in November 2015 and subsequent investigations in December 2015. The surface has been clipped by a mask (extent shown) to reduce interpolation edge effects. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Rowe, 2016; McWatters and Rowe, 2015). Diffusive properties of geomembranes used in cold climates have also been investigated in the laboratory and field studies (McWatters et al., 2016b, 2016c).

While vapour transport models are widely studied and used, ranging from generic 1D models to detailed 3D models (see Yao et al., 2013 for a review), there was no model that incorporated a vapour barrier. Until now, there has been no way to evaluate the performance of a specific barrier within a building design. When a building's indoor air quality does not meet standards, vapour barriers have often been recommended, but without quantitative modelling to assess the benefit that a barrier will have on indoor air quality. This is the first application using specific vapour barrier permeation properties in a contaminant transport model for indoor air investigation.

An additional consideration in this study was the integrity of the building's structure, because concrete building foundations in cold climates can suffer structural damage (e.g., cracking, shifting foundations) from the physical action of cyclic freezing and thawing. Vapour intrusion through concrete slabs will occur slowly by diffusion (through intact and cracked concrete) and more quickly by advection (through cracks and holes) (Hers et al., 2014; Yao et al., 2013). If the insulation were to fail in the CUB's foundation, the concrete may shift and crack subsequently increasing advective vapour intrusion. Maintaining a frozen subgrade below the concrete can minimise this and prolong the durability of the concrete material and the building (Shang et al., 2014). The CUB's foundation design includes a layer of extruded polystyrene (XPS) insulation beneath a slab-on-ground concrete floor to protect the subsoil from thawing due to heat transfer from the warm interior. The building design is dependent on XPS′ structural and insulation capacity. However, it was unknown how the XPS would perform while in close proximity to fuel and fuel vapours. This required further investigation.

If the contaminated soil below the future building posed a human health risk even with a vapour barrier installed, excavation of the source would be required and a suitable backfill material would be necessary. Clean soil is a limited resource at Antarctic stations (e.g., limited unfrozen ground and exposed rock) and therefore, an alternative backfill material was considered. This was soil partially remediated from a previous fuel spill and having undergone several years of biopile treatment (herein shortened to biopile soil) (McWatters et al., 2016a). It would offer a cleaner material than the contaminated soil currently within the CUB foundation, however, it also would need to undergo assessment using the new vapour intrusion model to establish if it posed a risk to human health.

Vapour intrusion modelling was conducted to allow decisions concerning continued construction, the type of soil foundation and required engineering controls. While the potential for hydrocarbon vapour intrusion is of concern when building on any previously contaminated site, there were additional considerations specific to this

Fig. 3. During the summer melt (late December 2015), fuel and water migrated further into the building site: a) LNAPL/water ingress into the building site); b) LNAPL layer above a SAB/water emulsion layer recovered from shallow test pit; c) LNAPL/water sitting above the surface ice on the water table; d) variety of phases of SAB fuel found; dissolved in groundwater, as LNAPL and in soil.

challenging, remote, cold region site that made the assessment more complex. These included: (i) protecting the building foundation by reducing contact between fuel and the sub-slab building thermal insulation; (ii) protecting the indoor air against the impacts of residual contamination or contaminated groundwater ingress; (iii) potential impact of future fuel spills; (iv) investigating risks associated with using biopile soil as backfill instead of clean fill; (v) and the need for quantitative consideration of different vapour barriers under Antarctic conditions.

This paper has three objectives. (1) To examine the potential impact on the CUB's indoor air concentrations for contaminants arising from the three soil foundation scenarios being considered: contaminated soil, backfilled clean soil, or biopile soil. (2) To use the new contaminant vapour transport model to assess the effect of the diffusive resistance of two different vapour barriers on indoor air quality and, therefore, the potential benefit of installing the engineered vapour barriers relative to each other and to no barrier when diffusive migration is from cold exterior to warmer interior temperatures. (3) To investigate the risk to the building foundation's integrity by studying the compatibility of the XPS insulation foam material with SAB diesel.

2. Scenarios examined and initial screening

2.1. Scenarios examined

Five scenarios were examined for managing the potential impact of the spill on indoor air quality.

- Scenario 1: assumes the building was constructed directly on the contaminated site and the hydrocarbon vapours originated from contaminated soil with only 0.2 m of unsaturated soil between the contaminant source and the building XPS.
- Scenario 2: assumes the hydrocarbon vapours originated from remaining (residual) contaminated groundwater after excavation of the contaminated soil and backfilling with clean soil quarried from the local environment.
- Scenario 3: assumes the excavated building footprint was backfilled with biopile soil and freeze back of soil would occur. Hydrocarbon vapours originate from the biopile soil.
- Scenario 4: assumes the excavated building footprint was backfilled with biopile soil as per Scenario 3 with additional hydrocarbon vapours originated from residual contaminated groundwater.
- Scenario 5: assumes the excavated building footprint was backfilled with biopile soil as per Scenario 3 with additional hydrocarbon vapours originated from a potential future spill.

Fig. 5 presents a conceptual site model of building layers for these five scenarios. Scenarios 1 and 3 were initially examined using a traditional screening tool that takes no account of the effectiveness of a vapour barrier. All scenarios were then examined using our more rigorous model that considers the effectiveness of different vapour barriers and is specific to the field conditions at Casey Station.

2.2. Vapour intrusion screening tool

The primary legislative framework for environmental issues in Antarctica is the Protocol on Environmental Protection to the Antarctic Treaty, known as the Madrid Protocol. The Madrid Protocol encourages best practice, but does not enforce or regulate air or soil quality guidelines or clean-up standards in Antarctica. In the absence of these guidelines, operating countries often either don't remediate, or use their domestic guidelines resulting in a range of remediation approaches. The relevant Australian national guideline is the National Environment Protection (Assessment of Site Contamination) Measure (NEPM) (NEPC, 1999). The NEPM provides health screening levels (HSLs) for the characterisation of human health risks via the vapour inhalation exposure pathway (and also direct contact pathways) from hydrocarbons in soils. The NEPM carries no legislative weight in Antarctica, and was not designed for use in polar regions; however, as it is the Australian national guideline, indoor air quality at an Australian station must meet HSLs to ensure worker safety when considering petroleum vapour intrusion. Whilst it is understood that the NEPM HSLs were not designed for use in polar environments, they were used in this study for an initial screening purposes, to establish if a gross risk to human health could be present. Results were also compared with the Canadian Council for

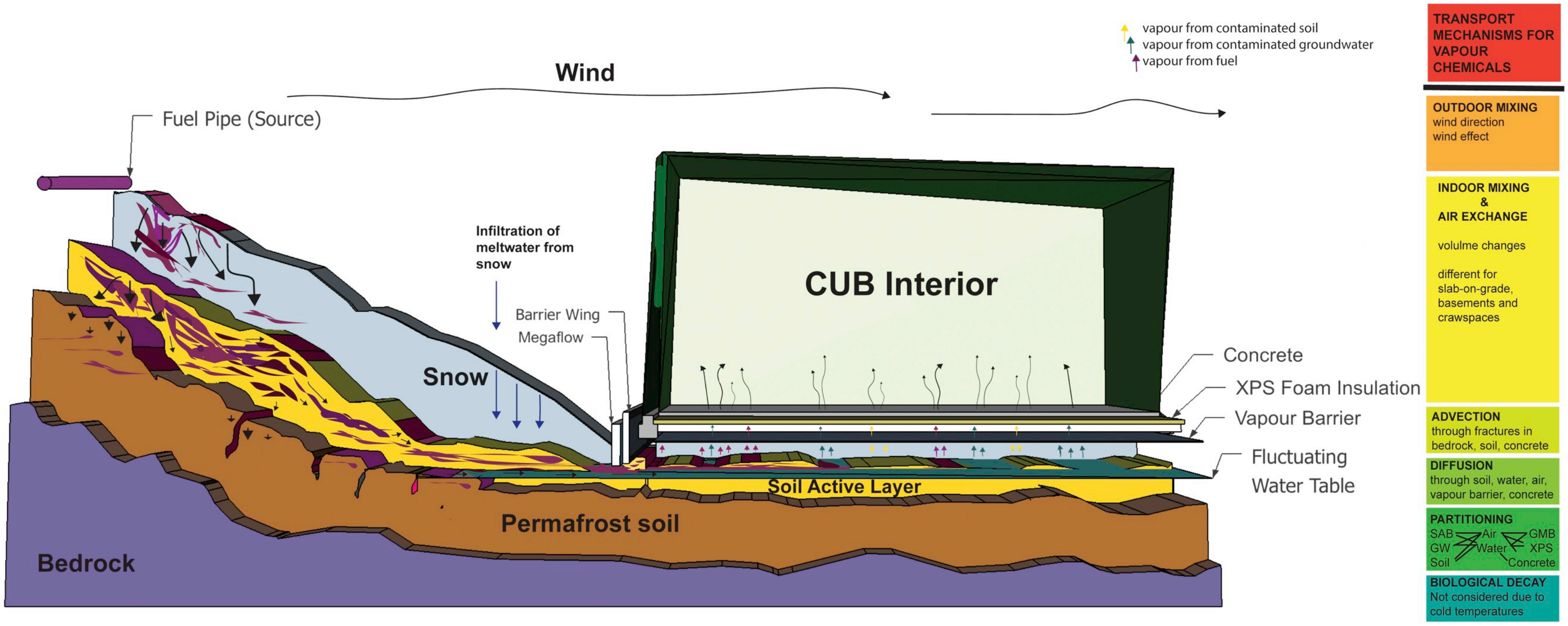

Fig. 4. Conceptual site model, with Eastern view, showing fuel migration from source to interior air space of building.

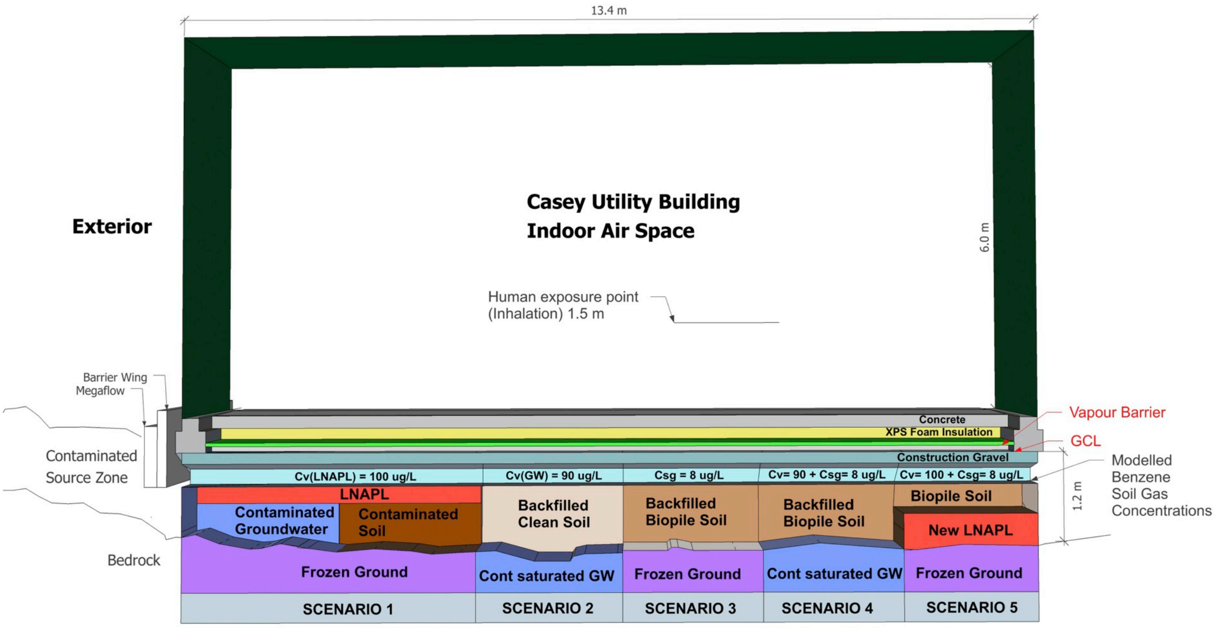

Fig. 5. Eastern view of building showing vapour intrusion modelling layers for Scenarios 1–5.

Ministers of the Environment (CCME) Tier 1 and Tier 2 governing objectives derived from a vapour intrusion screening tool (CCME, 2008). Similar limitations apply to the use of the CCME tool, although Canadian jurisdictions include permafrost soil building environments.

The CCME Tier 2 site-specific vapour intrusion screening tool was used to quantify the maximum TPH concentrations allowed in the soil below the building to meet indoor human health air quality guidelines. The tool is a spread sheet-based implementation of site-specific and default parameters to implement Tier 1 and Tier 2 of the Petroleum Hydrocarbon Canadian Wide Standards (CCME, 2008). Australian HSLs and CCME governing objectives are presented in Table 1. TPH analyses of the soil beneath the building foundation from November 2015 (Scenario 1) and the biopile soil proposed for backfill (Scenario 3) are also found in Table 1. For Scenario 1, TPH concentrations are above the screening levels and therefore it is not advisable to construct a building above this soil. For Scenario 3, the biopile soil levels for F1 (5.0 mg/kg) are below all three screening tool levels. However, for F2 (405 mg/kg), they are above Tier 1 and Australian NEPM health screening levels, but below the Tier 2 health screening levels. Since Tier 2 offers a more site-specific assessment, biopile soil is worthy of further consideration.

Table 1
Foundation soil quality standards for vapour inhalation (air quality human health standards and health screening levels).

Concentration $mg\ kg^{-1}$	Screening Tools			Scenario 1	Scenario 3
	Canada Tier 1	Canada Tier 2	Australia NEPM	CUB soil[a]	Biopile soil[b]
TPH (C_6-C_{40})				208 000	820
F1 (C_6-C_9)	30	78	45	48 800	5
F2 (C_{10}-C_{16})	150	670	110	155 700	400
F3 (C_{16}-C_{34})	300	N/A	N/A	32 400	405
F4 ($> C_{34}$)	2800	N/A	N/A	< 5	10

Note: Tier 1 values, are the generic standard value. Tier 2 values are the calculated values based on site-specific parameters entered into the screening tool. Note that the modelled F1 concentration (Tier 2 = 78 mg/kg) is more than the generic standard (Tier 1 = 30 mg/kg) (therefore less conservative). Output from CCME Tier 2 Model, source: CCME 2008. Australian NEPM values are from Schedule B1 Table 1A(3) Soil for Vapour Intrusion HSL A & HSL B for low density residential sand. F1 values are less BTEX. F2 values are less naphthalene.

[a] Highest measured concentration in soils sampled in November 2015.

[b] Average measured concentration in soils sampled in February 2015.

There are limitations to the Tier 2 health screening tool. For instance, contaminants are presented as fractions (F1-F4), not as individual compounds. More limiting, the tool cannot incorporate a vapour barrier, so it was only used to investigate indoor air quality assuming no vapour barrier. Also, the site-specific tool assumes a minimum distance of 0.3 m between contaminated soil and the building foundation, whereas, in our scenario, the contaminated soil is part of the foundation material (minimum distance from the backfilled soil to the XPS insulation materials is actually < 0.10 m). Lastly, the screening tool does not account for differences in indoor and outdoor air temperature and the subsequent effect on contaminant mass transport. For these reasons, a new vapour contaminant transport model was developed and applied.

3. Modelling approach

3.1. Vapour source

For each of the five scenarios, the mass flux through the building foundation layers (i.e., subsoil, insulation, concrete) to the indoor air space was calculated for four common volatile contaminants. Benzene and xylenes were selected to represent the ‘worst case’ scenarios as these compounds are highly mobile and have known diffusive properties through geomembranes (e.g., McWatters et al., 2016b). Benzene is also a known carcinogen (USEPA, 2008). Naphthalene and 2-methylnaphthalene (2-MN) were chosen as they are the most abundant volatile components of SAB and represent the ‘realistic case’ scenario, however no known diffusive properties have been quantified for geomembranes and they needed to be inferred.

Each scenario examined the effect of each engineering exposure control (i.e., different vapour barriers, air exchange system) on contaminant migration, employed either separately or in combination. The model was also used to investigate how colder temperatures influence contaminant migration.

The first source of contaminated vapour arises from the partitioning of chemicals dissolved in groundwater into soil gas (volatilisation). The vapour phase can be calculated based on Equation (1):

$$C_{vGW} = C_w \times H \tag{1}$$

where, C_{vGW} is the vapour concentration when no NAPL is present (mg/L); H is Henry's Law constant (−); and C_w is the chemical concentration in the groundwater (mg/L) where the maximum vapour concentration exists when C_w is equal to the chemical aqueous solubility, S (mg/L). All of these parameters are dependent on temperature.

The second source of contaminated vapour arises from the partitioning of chemicals in the soil into soil gas. The soil gas concentrations can be calculated based on Equation (2):

$$C_{sg} = \frac{H \times C_{soil} \times \rho_d}{\theta_w + (K_s \times \rho_d) + (H \times \theta_a)} \tag{2}$$

where C_{sg} is the vapour concentration released from the soil (mg/L); C_{soil} is the total soil concentration (mg/kg); ρ_d is the soil bulk density (kg/m^3); θ_w is the water-filled porosity in the soil (−); K_s is the soil partition fraction (m^3/kg); and θ_w is the air filled porosity in the soil (−).

The third source of contaminated vapour considered arises from the partitioning of LNAPL into soil gas, called vaporisation. This source generates the highest concentrations of chemicals in the vapour phase, based on Equation (3):

$$C_{vNAPL} = 1000\left(\frac{MW \times VP \times MF}{R \times T}\right) \tag{3}$$

where C_{vNAPL} is the vapour concentration when NAPL is present (mg/m^3); 1000 is conversion factor (mg/g); MW is chemical molecular weight (g/mol); VP is chemical vapour pressure (atm); R is universal gas constant (m^3 atm/K mol); and T is temperature (K); and MF is the mole fraction (−).

Petroleum fuels, such as SAB, have distinct analytical signatures, which reflect the type and length of carbon chains within the compounds. The analytical signature of SAB “peaks” between C_{12}-C_{14} (within the F2 range) but also contains smaller quantities of compounds in the upper F1 and lower F3 ranges (Table 1). BTEX are known to be a small fraction of the total hydrocarbons present in SAB. Whilst imperfect, this study used the mass fractions of compounds based on standard diesel taken from the CRC CARE Technical Report 10 (2013): 0.03% w/w benzene; 0.03% w/w xylene isomers; 0.26% naphthalene; 0.52% 2-MN. Mole fractions of each compound are calculated for the site temperature at 0 °C for soil and 1 °C for groundwater. Further information is in Supplementary Information.

The USEPA (2015) technical guidance document recommends considering a ‘reasonable worst case’ over a ‘representative’ exposure period as a starting point for a complex site, or when vapour concentrations are predicted to be low, as was the case with SAB. For the purposes of the model, the conservative ‘reasonable worst case’ scenario was assumed and initially set contaminant concentrations in the source across the entire building footprint. For different sources (contaminated soil, groundwater, biopile soil) the proportion of total hydrocarbon for each contaminant of primary concern was calculated (Supplementary Information). Initial hydrocarbon vapour concentrations arising from each source for Scenarios 1–5 are presented in Table 2.

3.2. Vapour intrusion modelling

A finite layer contaminant transport model (POLLUTE© v.7; Rowe and Booker, 2004) was used (for the first time) to evaluate the resistance that different vapour barriers can provide to contaminants entering a cold climate building. Two different vapour barriers were modelled and the results compared with the no vapour barrier scenario. This modelling is theoretical and based on the design conditions. It does not include vapour sampling validation based on as-built conditions.

POLLUTE is most commonly used for designing landfills where different barrier materials (with specific properties) can be incorporated into the design layers. It was originally designed for leachate (liquid), but has since been used for landfill gas (vapour) (McWatters et al., 2016b; Jones and Rowe, 2016; McWatters and Rowe, 2010). For this paper, it was configured for vapour intrusion into a building using soil vapour contaminants. Information regarding the boundary and initial conditions that can be modelled are found in Rowe et al. (2004) and Rowe and Booker (2004). When conventionally modelling a landfill the layers are all set with water as the reference fluid. In this new vapour modelling approach, POLLUTE was run with air as the reference fluid.

The model variables include contaminant source type (contaminated soil, contaminated water, and remediated soil), depth to source, vapour barrier (geomembrane) type, contaminant type, indoor air exchange ratio, power failures, and cracks in the concrete-slab-on ground.

Contaminant transport includes consideration of advection, diffusion, sorption and first order (e.g., biological) decay. Vapour transport through the soil to the building follows the governing advection-dispersion equation for contaminant transport (Equation (4)):

$$\frac{\partial c}{\partial t} = -v\frac{\partial c}{\partial z} + D\frac{\partial^2 c}{\partial z^2} - \frac{\rho K_d}{n}\frac{\partial c}{\partial t} - \lambda c \tag{4}$$

where c is concentration (g m^{-3}); t is time (s); z is the depth (m); v is the Darcy velocity (m^{3}s^{-1}); D is the dispersion coefficient (m^{2}s^{-1}); ρ is dry density of soil (g cm^{-3}); K_d is distribution/partitioning (sorption) coefficient (−); n is soil porosity (−); and λ is the biological decay constant of the contaminant (s^{-1}). Dispersion includes the effective diffusion coefficient and mechanical dispersion. Mechanical dispersion is negligible when there is a negligible advective velocity, but may dominate over diffusion when there is significant advection (Rowe et al., 2004). In this case, the modelling considered mechanical dispersion in and below the concrete slab to be negligible, but did consider it within the building for some cases. The modelling conservatively neglected biological decay as an attenuation mechanism given the cold temperatures and natural soil having low nitrogen levels that would inhibit biodegradation.

The CUB was modelled with a 6 m airspace over a building footprint of 28.8 m × 13.4 m. The engineered system below the building airspace comprised of (from top down): a 0.1 m-thick concrete slab; 0.1 m-thick XPS insulation layer; vapour barrier (as applicable); and a 0.2 m-thick unsaturated construction gravel layer. The entire building footprint below the engineered system was taken as a potential contaminant source. The mass flux of contaminants through the CUB foundation layers (subsoil, XPS, concrete) and vapour barrier (geomembrane) layers were calculated for the five scenarios as described below and shown in Fig. 5 and Table 2.

Scenario 1 modelled contaminant intrusion originating from 1 m of unexcavated unsaturated contaminated soil with a LNAPL layer of 0.01 m atop the soil. The soil had an interconnected gas porosity of 0.2, located directly below the engineered system. It was assumed that the soil vapour was in equilibrium with the LNAPL and at 0 °C. (Table 2). Partitioning of contaminant between the gas phase and the contaminated soil was modelled so that the entire available mass of contaminant was considered in the modelling (including its depletion as contaminant escaped).

Scenario 2 modelled contaminant intrusion originating from groundwater contamination that could pass through 1 m of clean soil over a three month thaw period, leaving residual LNAPL. The contaminant source represented 0.8 m^3 of contaminated groundwater per m^2 of CUB footprint during the three month “summer”. This contaminated groundwater was assumed to pass through/below initially unsaturated clean soil with an interconnected gas porosity of 0.3, below the engineered system. The contaminated groundwater was modelled by a finite mass boundary condition, recognising a limited mass of contaminants present in the groundwater was available for transport. The transport of vapour from the contaminated groundwater was modelled assuming that the vapour concentration was in equilibrium with the dissolved contaminant concentration in the groundwater (Table 2).

Table 2
Initial vapour concentrations of contaminant for Scenarios 1-5.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	Scenario 5
Condition	No excavation, build building.		Excavate, backfill with clean soil.		Excavate, backfill with biopile soil.		Excavate, backfill with biopile soil.	Excavate, backfill with biopile soil. New fuel spill under CUB.
Source Type	LNAPL layer above soil.		Groundwater with residual contaminants below backfill as below.		Biopile soil 1,000 mg/kg TPH		Residual contaminated groundwater below backfill.	LNAPL rests on underlying groundwater. Biopile soil re-contaminated.
Temperature (°C)	23	0	23	1	23	0	1	0
Initial concentration (μg/L)							Initial concentration values from Scenario 2 and 3	Initial concentration values from Scenario 1 and 3
Benzene	300	100	300	90	30	8.1		
Xylenes	90	20	90	20	45	9.1		
Naphthalene	2	0.3	2	0.3	1.5	0.2		
2-Methylnaphthalene	4	0.3	4	0.3	2	0.2		

Note: See Supplementary Information for calculation of initial concentrations.

Scenario 3 assumes that the bulk of the contaminated soil is removed and residual fuel and water is pumped from the excavation. Instead of backfilling with clean, quarried crushed Antarctic rock and soil, this option uses remediated biopile soil. Two previous fuel spills at Casey Station have undergone excavation and soil treatment using biopiles, resulting in significant reductions in hydrocarbons present in the soil (820 mg/kg TPH (Table 1)). Soil vapour concentrations used the same mole fractions for the four volatile chemicals as the other scenarios for consistency and conservatism (Table 2). Scenario 3 modelled contaminant intrusion originating from 1 m of unsaturated biopile soil, with an interconnected gas porosity of 0.2, used as backfill directly below the engineered system. This scenario models the contaminant source as soil vapour concentration in the air filled soil pores of the biopile soil. Partitioning of contaminant between the gas phase and the biopile soil was modelled so that the entire available mass of contaminant was considered in the modelling (including its depletion as contaminant escapes).

Scenario 4 was a 'worst case' combination of Scenarios 2 and 3. It modelled contaminant intrusion originating from 1 m of unsaturated biopile soil used as backfill directly below the engineered system (Table 4). It modelled partitioning of contaminant between the gas phase and the biopile soil. In addition, a contaminant source, represented by 0.8 m^3 of contaminated groundwater per m^2 of CUB footprint, was assumed to pass through beneath the CUB during the three month 'summer'. The airspace just below the biopile soil was assumed to be initially in equilibrium with underling contaminated groundwater as in Table 2.

Scenario 5 was a hypothetical 'future case' combining Scenarios 1 and 3 where a new fuel spill deposited a 0.01 m layer of LNAPL above the biopile soil. (Table 2). This thickness of fuel within the CUB building is equivalent to approximately 4000 L of fuel and is a similar volume to the 2015 fuel spill.

The model takes into account indoor air mixing effects through advection (due to fresh air inflow in the building) and diffusion/dispersions in the airspace. It calculated contaminant removal by the indoor air exchange system operating at 0.15 h^{-1} building volume exchanges per hour. The model also takes into account cumulative vapour accumulation in the building airspace if there is no air exchange (e.g., due to a power outage). The indoor air quality was established from the calculated indoor air concentrations at 1.5 m (the height of a nominal person).

3.3. Specific modelling considerations

3.3.1. Concrete slab

The slab was modelled as 100 mm-thick with a crack porosity was 0.005 (based on building slab design).

3.3.2. XPS

A 100 mm-thick XPS layer was laid in panels so the primary location for vapour migration was the airspace between the XPS panels. Accounting for the air gap between the panels, the average gas porosity was 0.006.

3.3.3. Vapour barrier

Two different products (Table 3) were considered for the vapour barriers in the building: a 0.56 mm-thick co-extruded LLDPE/EVOH/LLDPE geomembrane (denoted as VB1) and a 0.56 mm-thick LLDPE (VB2). Diffusive transport of contaminants (such as hydrocarbons) through a vapour barrier is characterised by the partitioning (S_{gf}), diffusion (D_g), and permeation (P_g) coefficients (e.g. Sangam and Rowe, 2001). Published coefficients were used as the basis for modelling diffusion through the two vapour barriers for benzene and xylenes (Table 5). Parameters were then calculated for specific field temperatures at Casey. Naphthalene permeation parameters used in this study were inferred from published data for analogous contaminants and their chemical relationships in the absence of relevant published values (Supplementary Information). 2-MN was not modelled through a vapour barrier as permeation parameters could not confidently be inferred.

3.3.4. Soil below XPS

In each case, the XPS was underlain by 0.2 m-thick gravel layer (15 mm; relatively uniformly graded) with an effective (i.e., available for vapour transport) porosity of 0.4 due to the gravel pores. In Scenario 1, the gravel was above contaminated soil with an effective interconnected gas porosity of 0.2 (allowing for some pores with frozen water blocking vapour transport) and an in-situ dry density of 1700 kg/m^3. In Scenario 2, the gravel was above a gravely fill with an effective gas porosity of 0.3. In Scenario 3, the gravel was underlain by biopile soil (sand sized distribution) with an effective porosity of 0.2, and a

Table 3
Selected properties of vapour barrier GMBs examined and compared.

Properties	Method ASTM	VB1	VB2
Thickness (mm)	D5199	0.56	0.56
Density (kg/m^3)	D792	0.94	0.92
Tensile strength at break (kN/m)	D6693	130	144
Elongation at break (%)	D6693	960	880
Puncture Resistance (N)	D4833	240	270
Oxidative induction time (min)	D3895	190	180

VB1 = 0.053 mm-thick co-extruded LLDPE/EVOH/LLDPE manufactured by Raven Industries, USA.
VB2 = 0.053 mm-thick LLDPE manufactured by Raven Industries, USA.
Properties are minimum values provided by the manufacturer except for OIT as measured by authors.

Table 4
Temperature adjusted layer properties for vapour intrusion modelling from source to receptor at temperatures reflective of CUB conditions in the cold environment using measured field temperatures and at standard uniform temperature of 23°C for comparison.

Conditions	Layer	Temp	Thickness	Porosity	$D_{benzene}$	D_{xylene}	D_{naph}	$D_{2\text{-}MN}$
		(°C)	(m)	(-)	(m^2/a)	(m^2/a)	(m^2/a)	(m^2/a)
Field Temperatures	Indoor air	23	6	1	280	240	190	160
	Concrete slab	7	0.1	0.005	73	64	49	43
	XPS	0	0.1	0.006	240	200	150	130
	Vapour Barrier	-7	0.0053	1	See Table 6			
	Gravel	-7	0.2	0.4	230	190	140	120
	Contaminated soil	-7	1.0	0.2	230	190	140	120
	Clean fill	-7	1.0	0.3	230	190	140	120
	Biopile soil	-7	1.0	0.2	230	190	140	120
Standard Temperatures	Indoor air	23	6	1	280	240	190	160
	Concrete slab	23	0.1	0.005	73	64	49	43
	XPS	23	0.1	0.006	280	240	190	160
	Vapour Barrier	23	0.0053	1	See Table 8			
	Gravel	23	0.2	0.4	280	240	190	160
	Contaminated soil	23	1.0	0.2	280	240	190	160
	Clean fill	23	1.0	0.3	280	240	190	160
	Biopile soil	23	1.0	0.2	280	240	190	160

compacted dry density of 1700 kg/m^3.

The contaminant in the Scenario 1 and Scenario 3 soils was represented by a distribution coefficient of 0.0025 m^3/kg for benzene, 0.0033 m^3/kg for xylene, 0.34 m^3/kg for naphthalene, and 0.97 m^3/kg for 2-MN based on the measured contaminant concentrations in the biopile soil and the calculated soil-vapour concentration (Table 2).

3.3.5. Temperature

Vapour transport modelling is often conducted assuming typical parameters at about 23 °C. In many areas of the world this is both convenient (since most parameters are obtained at room temperature) and appropriate (since 23 °C is a reasonable annual average temperature for many areas). However, in Antarctica the only zone likely to be at 23 °C is in the building. On an annual average basis, currently available data for Casey station suggest that the temperature: (i) at the centre of the concrete slab would be at 7 °C, (ii) the XPS would be 0 °C, (iii) below the XPS and the soil below this would be -7 °C. Thus the temperature at and below the vapour barrier was taken to be consistently -7 °C (Table 4). To provide a reference case, modelling was also conducted using diffusion coefficients at 23 °C (Table 5).

3.4. Summary of key modelling parameters

The thickness, porosity, and coefficients of hydrodynamic dispersion/diffusion for the various layers for the four contaminants of interest at the two modelled temperatures are summarised in Tables 2, 4 and 5.

3.5. Site specific indoor air quality criteria

Site-specific air quality criteria were derived for key non-threshold (cancerous) and threshold (non-cancerous) compounds. The criteria were derived using a back-calculation method based on standard risk derivation and characterisation for Australian contaminated sites and site-specific exposure parameters. Details of the derivation of the air quality criteria can be found in Supplementary Information and summarised in Table 6. The derived indoor air guideline concentrations are: benzene (21 $\mu g/m^3$) (the non-cancer threshold value being more conservative than the cancer non-threshold value of 70 $\mu g/m^3$); xylenes (150 $\mu g/m^3$); naphthalene (0.023 $\mu g/m^3$); 2-MN (0.045 $\mu g/m^3$). As an inhalation reference concentration is currently unavailable for 2-MN the derived criteria for naphthalene has been tentatively adopted in this instance for the purposes of discussion. The derived air quality criteria are based on site-specific user variables that consider chronic effects from long-term exposure (4 h/day, 365 days/year over 10 year period). However, an extremely conservative 'failure' rating was applied when modelled indoor air exceeded the derived criteria value. In effect, this treats the chronic based criteria value as an 'acute' exposure threshold.

Table 5
Permeation parameters (partitioning, S_{gf}, diffusion, D_g, and permeation, P_g, coefficients) for VB1 (3 layers) and VB2 (1 layers) based on aqueous conditions. Values were adjusted to vapour phase for modelling.

Temperature	Contaminant	VB1[a]				VB2[b]		
		LLDPE Outer Layers		EVOH Inner Layer[c]		LLDPE Layer		
		S_g	D_g	S_g	D_g	S_{gf}	D_g	P_g
		-	x10^{14} m^2/s	-	x10^{14} m^2/s	-	x10^{14} m^2/s	x10^{11} m^2/s
-7 °C	Benzene	20	2.5	2.4	0.09	21	14	0.3
	Xylenes	150	2.1	7.2	0.03	102	7.5	0.7
	Naphthalene [d]	300	1.8	9	0.02	300	3.1	2.5
23 °C	Benzene	180	8.7	12	0.3	200	48	9.6
	Xylenes	580	7.5	36	0.1	450	27	12
	Naphthalene [d]	800	6	45	0.05	800	11	8.8

[a] Based on McWatters and Rowe (2015a)
[b] Based on McWatters et al. (2016b)
[c] 38 mol% ethylene vinyl alcohol inner layer.
[d] Inferred values, see Supplementary Information

Table 6
Exposure specific indoor air guidelines.

Chemicals		EC Exposure concentration	C_g Exposure specific indoor air guideline concentration
		(μg/m^3)	(μg/m^3)
Benzene	Non-threshold	0.07	70
Benzene	Threshold	3.5	21
Ethylbenzene	Threshold	10	60
Xylenes	Threshold	25	150
Toluene	Threshold	130	760
Naphthalene	Threshold	0.0038	0.023
2-Methylnaphthalene[a]	Threshold	0.0075	0.045
Aliphatic $> C_8$-C_{10}	Threshold	600	3600
Aliphatic $> C_{10}$-C_{12}	Threshold	73	440
Aliphatic $> C_{12}$-C_{16}	Threshold	12	73
Aromatic $> C_8$-C_{10}	Threshold	19	120
Aromatic $> C_{10}$-C_{12}	Threshold	5.3	32
Aromatic $> C_{12}$-C_{16}	Threshold	1.0	6.0

[a] Assumes that compound specific inhalation reference concentration, RfC, is same as Naphthalene. No data exists for actual RfC of 2-methylnaphthalene

4. Results

4.1. Building material risk assessment

A quantitative and qualitative assessment of the XPS insulation foam was undertaken by submerging the foam in SAB. After 24 h, the foam sample's mass increased by 326% and dimensions decreased by 20%. Damage to the polystyrene polymer chains was noted by the softening of the exterior of the structure (See Supplementary Information). The foam began dissolving with light touch. From this, we conclude that SAB LNAPL causes structural degradation of the XPS foam. This is consistent with studies that have recorded structural degradation of XPS by diesel (Garcia et al., 2009; Karaduman et al., 2002). It was concluded that LNAPL at shallow depths within the CUB soil foundation poses a risk to the building by compromising the structural and insulation capacity of the XPS layer. This risk could be mitigated by using a welded vapour barrier that is resistant to SAB diesel. Constructing the building with insulation protected by a vapour barrier will lead to freezing of the underlying soil, but if the soil is unsaturated, vapour phase contaminants will remain mobile.

4.2. Human health risk assessment – benzene

In the following sections, benzene was assessed as that of primary interest with an allowable limit of 21 μg/m^3. All results that modelled an air exchange used an exchange rate of 0.15 h^{-1}. If the air exchange rate changed, new modelling would be required.

4.2.1. Scenario 1

Construction of the CUB building on the contaminated site was investigated as an option because of the need to complete the building exterior before the onset of winter with its associated very strong winds. Therefore, the worst case condition, with the building on the heavily contaminated soil, was examined for a number of cases both with and without a vapour barrier. With no vapour barrier (no VB), with no air exchange (e.g., due to a power failure), the regulatory limit would be exceeded in 1 day (Table 7). While this is a worst case, the situation is not much better with air exchange based on either pure diffusion or with dispersion at a level ten times higher than the diffusion coefficient in air. In both cases the regulatory limit is exceeded in 1 day and remains exceeded for an unacceptable 1000 days (diffusion only) or 550 days (with dispersion). Dispersion results in a lowering of the concentrations at a height of 1.5 m by a factor of three (i.e., ratio of the peak concentration with dispersion to that with only air diffusion is 0.33; Table 7). However, the peak impact is still high compared to regulatory limits. Fig. 6 highlights this case (no VB results), with the concentration increasing relatively rapidly in all cases and remaining above the guideline limit (Fig. 6) for a protracted period even with air exchange and dispersion.

When VB2 was modelled, it took 4 days before the regulatory limit was reached with no air exchange, 5 days for air exchange and 7 days for air exchange with dispersion. The peak concentration in the building was lower than for the no VB case and there was a 20% shorter period of exceedance (Table 7; Fig. 6). Thus VB2 with dispersion and air exchange did not resolve the issue, although it did substantially reduce the exceedance period.

The co-extruded VB1 substantially slowed the ingress of benzene. The air exchange system would need to be un-operational for 20 days before regulatory limits were reached; this is an unlikely but possible situation. If only diffusive mixing in the building is considered, the air exchange rate was sufficient to maintain acceptable indoor air quality (Table 7 and Fig. 6). Allowing for ten-fold dispersion in the airspace of the building, the regulatory limit was easily met at all times. (Table 7; Fig. 6).

4.2.2. Scenario 2

In Scenario 2, contaminated soil is removed and replaced with clean (uncontaminated)soil. It assumes an unfrozen zone of contaminated groundwater below the CUB during the summer. For this scenario, it would take 1 day, 30 days and 6 days to exceed the regulatory requirements, given no air circulation for no VB, VB1 and VB2, respectively (Table 8). Repairing the air exchange system or a power failure may well be achievable in 6 days and certainly is likely to have been achieved within 30 days. With air exchange set at 0.15 h^{-1} and no VB, the regulatory limit was reached within 2 days, and exceedance continued for 1250 days. For VB2, the regulatory limit was reached within 10 days and exceedance continued for 1500 days (Table 8 and Fig. 7). Thus, neither case was considered a viable option based on air quality being over the regulatory limit for such a sustained period. However, VB1 easily met the regulatory limit with 0.15 h^{-1} air exchange, even with no dispersion in the building. From the perspective of human health risk, the installation of VB1 in Scenario 2 is thus considered a viable option.

4.2.3. Scenario 3

In Scenario 3, contaminated soil is removed and replaced with biopile soil. Residual fuel and water is pumped from the area. In the absence of a VB and no air exchange, the regulatory limit would be exceeded in 1 day. Inclusion of VB2 allows 5 days to recommission the air exchange unit before the regulatory limit is reached. VB1 provides 35 days with no air exchange system before the regulatory limit was reached. Once air exchange is included in the model, the concentration in the airspace was very low and the regulatory limit was met for as long as the air exchange is maintained (Table 8; Fig. 8). From the perspective of human health risk, the installation of VB1 in Scenario 3 is thus considered a viable option.

4.2.4. Scenario 4

This scenario combined Scenarios 2 and 3 as previously described. In the absence of a VB and no air exchange, the regulatory limit would be exceeded in 1 day (Table 8). Inclusion of VB2 allows for 4 days and VB1 provides 30 days to re-establish air exchange. With air exchange and no VB, indoor airspace concentrations would still exceed the limit for benzene after 1 day, and extend to about 1750 days, due to residual fuel in the groundwater. With VB1 and air exchange, the regulatory limit was met for as long as the air exchange is maintained (Table 8; Fig. 9).

Based on the modelling results from these four scenarios, re-using biopile soil as backfill and installing VB1 was considered the best

Table 7
Scenario 1 with contaminated soil at expected field temperatures. Includes time to violation of standard, and peak concentration, C_p, and time to end of violation (where applicable).

	No Air Exchange		Air Exchange with diffusion		Air Exchange with dispersion			Dispersion /diffusion
	Time to violation, d_1 (d)	C_p (µg/m^3)	Time to violation, d_1 (d)	End of violation, d_2 (d)	C_p (µg/m^3)	Time to violation, d_1 (d)	End of violation, d_2 (d)	
No VB	1	540	1	1 000	180	1	550	0.33
VB1	20	5.9	∞	∞	1.9	∞	∞	0.32
VB2	4	230	5	1 700	73	7	1 000	0.32

NOTE: A time to violation, ∞, means standard concentration was never exceeded; d = day.

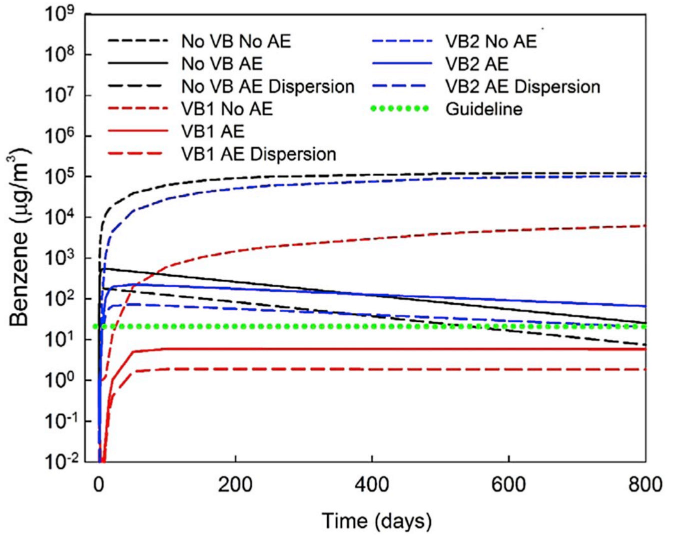

Fig. 6. Benzene concentrations with time for three different scales for Scenario 1 at field temperatures – LNAPL present.

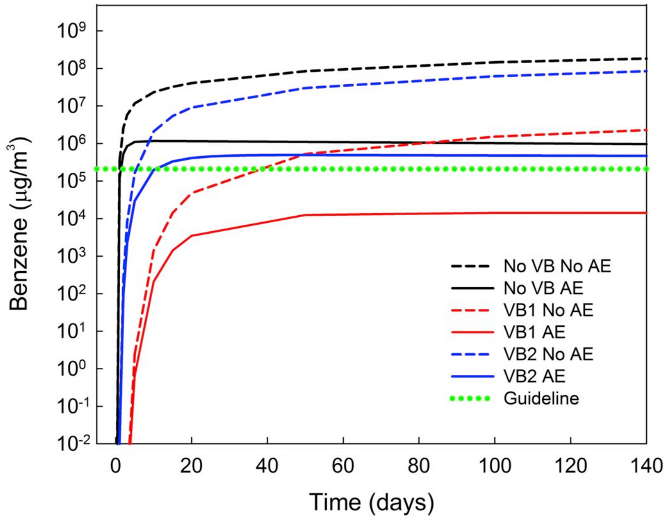

Fig. 7. Benzene concentrations plotted with time for Scenario 2 at field temperatures - Contaminated groundwater below clean soil.

Table 8
Results for scenario modelling showing time to violation of standard indoor air threshold, peak concentration, C_p, and time to end of violation (where applicable).

Scenario	VB Type	No Air Exchange	Air Exchange with diffusion		
		Time to violation, d_1 (d)	C_p (µg/m^3)	Time to violation, d_1 (d)	End of violation, d_2 (d)
2	No VB	1	115	2	1250
	VB1	30	1.4	∞	∞
	VB2	6	49	10	1500
3	No VB	1	120	2	500
	VB1	35	1.3	∞	∞
	VB2	5	51	10	600
4	No VB	1	120	1	1750
	VB1	30	1.4	∞	∞
	VB2	4	52	7	1500
5	No VB	1	670	1	700
	VB1	25	7.3	∞	∞
	VB2	3	88	7	600

Scenario 2 - removal of contaminated soil and replacement by clean soil, underlain by groundwater with residual contaminants. Scenario 3 - removal of contaminated soil and its replacement with biopile soil. Scenario 4 - biopile soil underlain by contaminated groundwater. Scenario 5 - removal of contaminated soil and replacement by biopile soil. All scenarios modelled at expected field temperatures.

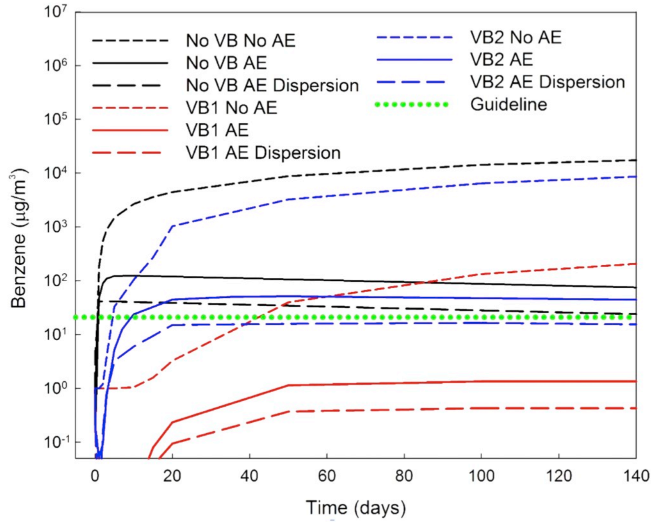

Fig. 8. Benzene concentrations plotted with time for Scenario 3 at field temperatures – remediated soil below the engineered system.

option, subject to confirmation that the other key contaminants also met regulatory requirements.

4.2.5. Effect of temperature

To examine the effect of temperature, the calculations discussed above for Scenario 3 were repeated using the same parameters as in Table 5, but at 23 °C (Table 9). With no VB, the room temperature model gave a shorter time (1 day) to regulatory violation than at field

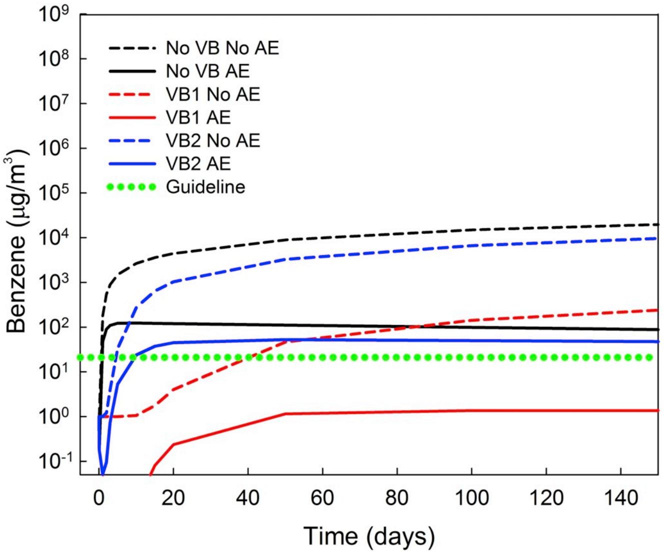

Fig. 9. Benzene concentrations plotted with time for Scenario 4 at field temperatures – remediated soil below the engineered system and contaminated ground water.

Table 9
Effect of temperature for Scenario 3 with biopile soil below building foundation and air exchange at 0.15h^{-1} for two different temperatures: expected field temperatures and room temperature.

	Field temperatures			Room Temperature 23°C		
	C_p (µg/m^3)	Time to violation, d_1 (d)	End of violation d_2 (d)	C_p (µg/m^3)	Time to violation, d_1 (d)	End of violation, d_2 (d)
No VB	120	2	500	300	1	1000
VB1	1.3	∞	∞	21	50	500
VB2	51	10	600	290	2	900

temperature (2 days) and a much longer period of violation (1000 versus 500 days). However, both models suggest that a vapour barrier was needed. Using VB2, room temperature modelling resulted in unsatisfactory airspace concentrations between day 2 and 900 due to the faster release of contaminants. Modelled at lower temperatures, VB2 was more effective and contaminant release was slower, however, the concentration in the CUB still had an unacceptable impact (with air exchange). Using VB1, room temperature results gave an unacceptable impact between 50 and 500 days with a concentration of 21 µg/m^3 at the regulatory limit. If indoor air dispersion was included, installing VB1 would result in acceptable air quality (i.e., below the exposure specific indoor air guideline concentration).

4.3. Human health risk assessment – other contaminants

As part of the initial evaluation of leaving the contaminated soil in place (Scenario 1) and assessing the viability of replacing the contaminated soil with remediated biopile soil (Scenario 3), calculations were performed to check the other key contaminants with air exchange set at 0.15 h^{-1} (Table 2).

In Scenario 1 with no VB, concentrations of naphthalene and 2-MN exceeded the indoor air guideline (Table 10). With the installation of VB1 or VB2, naphthalene still exceeded guidelines, assuming no significant dispersion in the airspace. Thus naphthalene is the critical contaminant for Scenario 1. For xylenes (c_{SG} = 20000 µg/m^3, c_{max} = 150 µg/m^3), indoor air concentrations were below guideline limits under all conditions. However, whist xylenes had a low mobility and impact, they were very persistent and had the longest presence below the building.

For Scenario 3, with no VB and VB2, only benzene was a problem (the critical contaminant) with respect to indoor air quality standards. All vapour barriers (VB1 and VB2) gave acceptable results for xylenes, naphthalene and 2-MN.

4.4. Scenario 5

Scenario 5 assumes a hypothetical future fuel spill, with 0.01 m layer (above the water table) of LNAPL re-contaminating the previously remediated biopile soil underneath the building (Table 8; Fig. 10). For this case, only VB1, under the circumstance of 0.15 h^{-1} air exchange will provide sufficient protection to meet the applied indoor air quality guidelines.

5. Discussion

Preventing and subsequently managing fuel spills anywhere in Antarctica is challenging given the extreme environment and logistical constraints. At Casey Station, there were also challenges due to: the presence of variable but generally shallow fractured bedrock; granular and permeable soils where soils are present and not frozen; unsaturated permafrost soils (i.e., they retain vapour permeability and potentially some hydrocarbon permeability when frozen); thaw in permafrost soils when uncovered for building works; and a seasonal pulse (< 3 months) of shallow ground and surface waters. The summer active-layer hydrology is difficult to investigate and interpret. In addition, the exact volume of fuel released in this spill was unknown. Due to operational constraints, it was not possible to delay construction of the CUB and remediate the entire site including the up-gradient source area before construction. Thus, early in the fuel spill response, a funnel-and-gate permeable reactive barrier (PRB) was installed up-gradient of the CUB footprint to help direct the plume away from the building. The human health risk assessment modelling vapour intrusion undertaken in this study informed the next steps for this contaminated site.

The finite layer transport analytical model calculated the mass transport of key contaminants benzene, xylenes and naphthalene through vapour barriers and the building foundation for various initial source concentrations and phases. Aerobic biodegradation within the subsurface soil can attenuate vapour and therefore substantially reduce risks (DeVaull, 2007; Lahvis et al., 2013). However, this natural process is severely limited in cold regions due to the combination of low temperature, low moisture, low nutrients and low organic carbon, and therefore cannot be relied on to reduce vapour intrusion (Gore et al., 1999; Hers et al., 2014). Thus, colder temperatures do not necessarily decrease the risks to human health. Cold temperatures can also slow the release of contaminants from the soil or water to the vapour phase and diffusive transport, but this may increase the contaminating lifespan of the source mass. For these reasons, biodegradation of each contaminant was not considered in the vapour this intrusion modelling for the Antarctic environment (although the model itself readily allows its considering if it was appropriate to do so in the future).

The approach adopted herein represents the first use of a model developed explicitly for modelling vapour migration though a layer of plastic (the vapour barrier) and into a building from contaminated/remediated soil. Commonly, when an attempt to model a vapour barrier is made using existing tools developed for soil, the vapour barrier is modelled as a soil layer. This is erroneously done and does not recognize that the migration of contaminants through a vapour barrier must be modelled differently to the unsaturated pore structure of a soil. In particular, consideration of migration through an intact vapour barrier as examined here requires consideration of partitioning of the contaminant to the vapour barrier as well as diffusion through the amorphous phase of the vapour barrier and partitioning out of the vapour barrier. It needs to be recognised that the controlling

Table 10
Time to indoor air concentration guideline violation – effect of contaminant type at expected field temperatures with air exchange for Scenario 1 and Scenario 3.

	Benzene			Xylenes			Naphthalene			2-MN		
	C_p (μg/m^3)	d_1 (d)	d_2 (d)	C_p (μg/m^3)	d_1 (d)	d_2 (d)	C_p (μg/m^3)	d_1 (d)	d_2 (d)	C_p (μg/m^3)	d_1 (d)	d_2 (d)
Threshold	21			150			0.023			0.045		
Scenario 1												
No VB	540	1	1 000	34	∞	∞	2.2	< 1	> 10 000	0.09	< 1	> 10 000
VB1	5.9	∞	∞	1.8	∞	∞	1.9	< 1	3	-	-	-
VB2	230	5	1 700	23	∞	∞	2.6	< 1	3	-	-	-
Scenario 3												
No VB	120	2	500	15	∞	∞	0.02	∞	∞	0.01	∞	∞
VB1	1.3	∞	∞	0.71	∞	∞	0.003	∞	∞	-	-	-
VB2	51	10	600	10	∞	∞	0.02	∞	∞	-	-	-

d_1 = time to violation
d_2 = end of violation

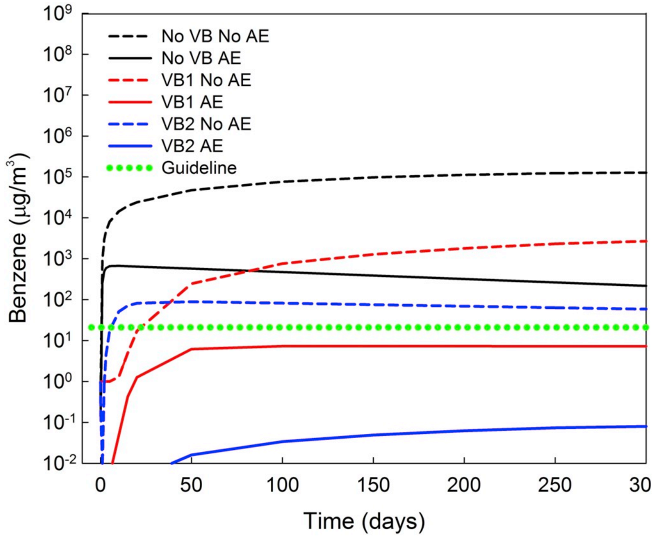

Fig. 10. Benzene concentrations plotted with time for Scenario 5 at field temperatures for a new fuel spill under building. Benzene concentrations plotted with time plus contaminated ground water.

partitioning coefficient and the diffusion coefficient in the vapour barrier itself are very sensitive to both the type of membrane (e.g., polymer, manufacturing process) and the contaminant being considered. Previous approaches do not effectively distinguish between the performances of different vapour barriers whereas the present approach permits this comparison.

All modelled scenarios establish there is lower risk to indoor air quality when using a properly installed vapour barrier in the building foundation. Vapour barriers are relatively thin, but their polymer structure provides a diffusive contaminant barrier. Common polymers are high density polyethylene (HDPE) or LLDPE. Polyethylene is an excellent barrier to water and soluble ions but is permeable to hydrocarbons (Sangam and Rowe, 2001; Feldman, 2002; Jones and Rowe, 2016). In our modelling, VB1 (0.53 mm LLDPE/EVOH/LLDPE co-extruded vapour barrier) performed better than VB2, a standard LLDPE. VB1 has outer LLDPE layers, but an interior EVOH thin-film layer. This EVOH is an excellent hydrocarbon barrier but is severely affected by moisture (McWatters and Rowe, 2018). To overcome these challenges, the hydrophilic EVOH layer is laminated with exterior layers of the hydrophobic polyethylene to form composite vapour barrier. That is why the co-extruded PE/EVOH/PE geomembranes have been shown to provide a superior barrier to hydrocarbons over single layer LLDPE and HDPE geomembranes in laboratory studies (McWatters and Rowe, 2010, 2015, 2018), and also now in vapour intrusion modelling. Furthermore, a vapour barrier will only provide a sufficient diffusive barrier to contaminant intrusion if it is welded and installed correctly, free from holes and protected from objects that may puncture it. It is noted, that geomembranes in contact with free phase fuels can be damaged. At this site, contact between LNAPL and vapour barriers could be mitigated through diverting and/or pumping groundwater during summer until the subgrade has frozen.

Benzene and xylenes have the most accurately known permeation parameters for vapour barriers as they are the most studied (McWatters and Rowe, 2015; Sangam and Rowe, 2001). Naphthalene and 2-MN are the best compounds to reflect the volatile component of diesel, however, permeation through vapour barriers and geomembranes have not been previously studied. Future research will give more accurate results and increase the confidence in predicting vapour intrusion for fuels with a relatively high naphthalene concentration.

The modelling of vapour intrusion for contaminants originating from the onsite LNAPL in the contaminated soil (Scenario 1) indicated that, if left as part of the building foundation without a vapour barrier, it would pose a risk to human health by vapour inhalation. Thus it would need to be excavated and replaced unless adequate mitigation could be achieved by vapour barriers. The modelling showed that only the installation of VB1 offered a potentially acceptable means of retaining the contaminated soil in the foundation. This gave acceptable result provided the 0.15 h^{-1} air exchanges were maintained and allowed 20 days for repair of the air exchange system if it ceased to function. However, given the remote nature of the Antarctica station and the fact that it is essentially inaccessible for 8 months of the year with a staff having to make-do without external assistance or equipment replacement, it was considered that although the risk of an air exchange shutdown for the 20 days was quite low, the option of building over the contaminated soil (Scenario 1) was not recommended given that reasonable alternatives were available. The replacement of the contaminated soil with clean (uncontaminated), quarried and crushed Antarctic rock and soil (Scenario 2) represented viable alternative from an air quality health and safety perspective but would involve environmental impacts from extracting the very limited resource. It was not recommended given that reasonable alternatives were available. The replacement of the contaminated soil with biopile soil (Scenario 3), with the use of VB1 was sufficiently protective of the applied human health guideline values. It also provided a good environmental outcome by reusing previously impacted soil and avoiding unnecessary quarrying of pristine rock and soil. Risks associated with the reuse of biopile soil examined in this study pertain to possible residual contaminant concentrations in the soil, their likely toxicity and mobility, transport mechanisms (e.g. water, vapour, seasonally unfrozen ground) and the sensitivity of the receiving environment in terms of indoor air quality.

All four critical contaminants met regulatory requirements. The indoor air quality risks of using this soil is very low because the volatile components that once existed in this soil were largely removed from the soil during the biopile treatment process, and are likely to be lower than modelled here. However, even with excavation of the contaminated soil from the site and backfilling with biopile soil, the modelling indicates additional engineering controls (i.e., use of VB1 and air exchange) are required to meet the applied human health guidelines. When additional controls are included in the vapour intrusion models, the risk to human health is reduced to well below the applied regulatory limits.

Scenario 5 presented a safeguard for the entire CUB lifetime because it evaluates the possible concentrations that the building may experience in the event of a future (hopefully, but not necessarily, hypothetical) spill. Based on this, the engineering controls put in place for the CUB were designed recognising that, in the case of a future spill, it will not be possible to access or excavate the area under the building. Using an appropriate EVOH vapour barrier gives added insurance against the possible occurrence of future fuel spills in addition to protection from residual contamination. The benefit of added assurance and protection outweighs the installation cost.

The modelling showed that in all cases, air exchange significantly reduced vapour concentrations in the building and hence the impact of vapour migration on the health of building occupants. Modelled indoor air concentration results show that when no air exchange occurs within the building, the contaminant levels build up over time. This could readily happen during a power outage or a mechanical failure of the air exchange systems. In the Antarctic environment, pressure differences between the indoor and outdoor air arising from strong winds, blizzard conditions, or snow blocking the air vents can also put the air exchange system at risk of failure.

Active or passive venting from below the building is not a viable/reliable option. Infiltration is generally minimal in modern Antarctic structures because small holes would allow snow entry to the interior during blizzards. Natural ventilation through doors is minimised, with doors only opening for entry infrequently. Similarly, there are no opening windows. The planned CUB building's air exchange relies almost totally on mechanical ventilation where air movement is controlled by fans. In reality, indoor air exchange does not achieve perfect mixing of the indoor air as walls, doors and other installed components can restrict air circulation. As the building is intended to house a wastewater treatment facility, air from this area is not recycled through the entire building. Modelling indicates the building air exchange should be maintained at an exchange rate of $0.15\ h^{-1}$. If air exchange is not maintained at this rate, the modelled contaminant concentrations increase.

5.1. Outcomes

The findings presented in this study were used to minimise possible future vapour intrusion human health risks. The applied fuel spill response included removing LNAPL, excavating contaminated soil and pumping and treating contaminated groundwater. Remediated biopile soil (350 t) was used as backfill material for the building foundation (as per Scenario 3). The exterior of the building was constructed before the winter season (Fig. 11a). In the following summer, from mid-November to mid-January, the seasonal groundwater level fluctuated from 0.0 m to 0.2 m below the new soil surface (Fig. 11b and c). This water showed evidence of contamination (sheen), making Scenario 4 a realistic scenario for this site. The building foundation layers were installed during the summer period including: a geosynthetic protection layer (Fig. 11d); welded vapour barrier (VB1) (Fig. 11e); XPS insulation wrapped in a second layer of VB1 for protection (Fig. 11f); and concrete poured in sections. During this same summer season, the much of contaminated soil up gradient of the CUB was excavated, thereby decreasing future contaminant ingress under the building foundation. Monitoring systems were installed in the sub-slab area to enable future vapour monitoring and ensure that engineering controls continue to perform as specified.

This paper evaluated the risk of reusing the biopile soil in the context of human health indoor air quality. It does not investigate other human health risks (i.e. dermal exposure, ingestion) nor other receptors (e.g. animals, microorganisms) and pathways (e.g. ecotoxicological). These other factors are to be considered in a future larger risk assessment framework.

6. Conclusions

This paper addressed three objectives. Firstly, it has been shown that, the construction of a building over the contaminated site (Scenario 1) could lead to undesirable impacts. Contaminant modelling led to a management decision to excavate the contaminated soil and backfilling with previously remediated biopile soil (Scenario 3). As this study showed, the indoor air quality regulatory limits were likely to be met, for any of the four contaminants, if building air exchange is maintained at $0.15\ h^{-1}$ and the specified vapour barrier, VB1 (a 0.5 mm-thick co-extruded LLDPE/EVOH/LLDPE geomembrane), was properly installed in the building foundation. Residual contamination in the groundwater was also modelled (Scenario 2 and 4) and results showed that risks to indoor air quality were low, if the building air exchange was maintained (with typical small periods of down time for maintenance and repair or the air exchange system) and the specified vapour barrier was used.

Secondly, a vapour intrusion model was developed to include and evaluate the resistance that different vapour barriers provide to hydrocarbon vapours from entering a planned building. This vapour intrusion model was also designed specifically to accommodate the modelling of the cold Antarctic environment, including specific field temperatures and a seasonal groundwater pulse. The main findings from the modelling show that VB1 was consistently superior at reducing diffusive migration of benzene, xylenes and naphthalene compared to a more traditional LLDPE geomembrane. It also showed that adequate air exchange is required to ensure indoor air quality meets the applied human health guidelines.

Thirdly, it was shown that building foam insulation material, XPS, was impacted by contact with SAB diesel. To preserve the insulation layer, and maintain frozen temperatures below the building, the XPS was wrapped in a second layer of the same vapour barrier to minimise the risk of damage to the insulation by SAB in either liquid or vapour phases.

Installation of a suitable vapour barrier and maintaining building air exchange present the best combination of risk mitigation measures to safely manage the construction of building on this Antarctic contaminated site. This vapour intrusion model can be applied to other building sites impacted by a fuel spill if fuel concentrations in the soil and groundwater below the building are known or can be estimated. The model will give an indication of when a building's indoor air space would be at risk from contaminant intrusion, and can be compared to any relevant guidelines.

Acknowledgments

This work was conducted under Australian Antarctic Science grants 1136 and 4036, and insurance funding. The authors acknowledge the hard work and assistance of L. Wise, D. Terry, B. Sfiligoj, G. Lagerewskij, V. Di Battista and the past and present persons at the Australian Antarctic Division and Casey Station, and of research collaborators from University of Melbourne, Macquarie University, Monash University, and Queen's University. The authors acknowledge the specialist technical advice from Nick Woodford, Coffey Services Australia Pty Ltd.

Fig. 11. a) Contaminated soil was excavated and backfilled with remediated biopile soil before exterior building structure was constructed; b) biopile soil and groundwater at surface of soil in November; c) biopile soil and groundwater below ground level in December; d) protective layer (white) above construction gravel and below welded VB1 (green); e) VB1 across entire building; f) XPS insulation layer above VB1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.07.092.

References

Aislabie, J.M., Balks, M.R., Foght, J.M., Waterhouse, E.J., 2004. Hydrocarbon spills on Antarctic soils: effects and management. Environ. Sci. Technol. 1265–1274.

Barnes, B., Biggar, K., 2008. Movement of petroleum through freezing and frozen soils. In: Filler, D., Snape, I., Barnes, D. (Eds.), Bioremediation of Petroleum Hydrocarbons in Cold Regions. Cambridge University Press, Cambridge, pp. 55–68.

CCME, 2008. Canada-wide Standard for Petroleum Hydrocarbons (PHC) in Soil – Spreedsheet Model v. 2.1 Canadian Council of Ministers of the Environment.

CRC CARE, 2013. CRC CARE Technical Report 10: Health Screening Levels for Petroleum Hydrocarbons in Soil and Groundwater. Cooperative Research Centre for Contamination Assessment and Remediation of the Environment.

DeVaull, G.E., 2007. Indoor vapour intrusion with oxygen-limited biodegradation for a subsurface gasoline source. Environ. Sci. Technol. 41 (9), 3241–3248.

DeVaull, G.E., Ettinger, R., Gustafson, J., 2002. Chemical vapour intrusion from soil or groundwater to indoor air: significance of unsaturated zone biodegradation of aromatic hydrocarbons. Soil Sediment. Contam. 11 (4), 625–641.

Feldman, D., 2002. Polymer barrier films. J. Polym. Environ. 9 (2), 49–55.

Fitzpatrick, N.A., Fitzgerald, J.J., 1996. An Evaluation of Vapor Intrusion into Buildings through a Study of Field Data. C Contaminated Soils University of Massachusetts at Amherst, October.

Fitzpatrick, N.A., Fitzgerald, J.J., 2002. An evaluation of vapor intrusion into buildings through a study of field data. Soil Sediment. Contam. 11, 603–623.

Garcia, M.T., Gracia, I., Duque, G., de Lucas, A., Rodríguez, J.F., 2009. Study of the solubility and stability of polystyrene wastes in a dissolution recycling process. Waste Manag. 29 (6), 1814–1818.

Gore, D.B., Revill, A.T., Guille, D., 1999. Petroleum hydrocarbons ten years after spillage at a helipad in Bunger Hills, East Antarctica. Antarct. Sci. 11, 427–429.

Hers, I., Jourabchi, P., Lahvis, M.A., Dahlen, P., Luo, H., Johnson, P., DeVaull, G.E., Mayer, K.U., 2014. Evaluation of seasonal factors on petroleum hydrocarbon vapor biodegradation and intrusion potential in a cold climate. Ground Water Monit. Rem. 34 (4), 60–78.

Johnson, P.C., 2005. Identification of application-specific critical inputs for the 1991 Johnson and Ettinger vapor intrusion algorithm. Ground Water Monit. Rem. 25 (1), 63–78.

Johnson, P.C., Ettinger, R., 1991. Heuristic model for predicting the intrusion rate of contaminant vapors into buildings. Environ. Sci. Technol. (25), 1445–1452.

Jones, D.D., Rowe, R.K., 2016. BTEX migration through various geomembranes and vapour barriers. Geotech. Geoenviron. Eng. 142 (10), 1–12.

Karaduman, A., Simsek, E.H., Cicek, B., Bilgesu, A.Y., 2002. Thermal degradation of polystyrene wastes in various solvents. J. Anal. Appl. Pyrol. 62, 273–280.

Lahvis, M.A., Hers, I., Davis, R., Wright, J., DeVaull, G., 2013. Vapor intrusion screening at petroleum UST sites. Ground Water Monit. Remed. 33 (2), 53–67.

McAlary, T., Provoost, J., Dawson, H.E., 2011. Vapor intrusion. In: Swartjes, F.A. (Ed.), Dealing with Contaminated Sites. From Theory towards Practical Application. Springer, Dordrecht, NL.

McWatters, R., Rowe, R.K., 2010. Diffusive Transport of VOCs through LLDPE and two coextruded geomembranes. J. Geotech. Geoenviron. Eng. 136 (9), 1167–1177.

McWatters, R., Rowe, R.K., 2015. Permeation of volatile organic compounds through EVOH thin-film membranes and coextruded LLDPE/EVOH/LLDPE geomembranes. J. Geotech. Geoenviron. 141 (2), 1–15.

McWatters, R., Rowe, R.K., 2018. Barrier permeation properties of EVOH thin-film membranes under aqueous and non-aqueous conditions. Geotext. Geomembr. 46 (4), 529–541.

McWatters, R.S., Wilkins, D., Spedding, T., Hince, G., Raymond, B., Lagerewskij, G., Terry, D., Wise, L., Snape, I., 2016a. On site remediation of a fuel spill and soil reuse in Antarctica. Sci. Total Environ. 571, 963–973.

McWatters, R.S., Rowe, R.K., Rutter, A., 2016b. Geomembrane applications for controlling diffusive migration of petroleum hydrocarbons in cold region environments. J. Environ. Manag. 181, 80–94.

McWatters, R.S., Rowe, R.K., Wilkins, D., Spedding, T., Jones, D.D., Terry, D., Hince, G., Wise, L., Gates, W.P., Bouazza, A., Di Battista, V., Shoaib, M., Snape, I., 2016c. Geosynthetics in Antarctica: performance of a composite barrier system to contain hydrocarbon-contaminated soil after 3 years in the field. Geotext. Geomembr. 44, 673–685.

Mohn, W., Stewart, G., 2000. Limiting factors for hydrocarbon biodegradation at low temperature in Arctic soils. Soil Biol. Biochem. 32, 1161–1172.

NEPC, 1999. National Environment Protection (Assessment of Site Contamination) Measure. (as amended 2013).

Ping, C.L., Jastrow, J.D., Jorgenson, M.T., Michaelson, G.J., Shur, Y.L., 2015. Permafrost soils and carbon cycling. Soil 1, 147–171.

Provoost, J., Reijnders, L., Swartjes, F., Bronders, J., Seuntjens, P., Lijzen, J., 2009. Accuracy of seven vapour intrusion algorithms for VOC in groundwater. J. Soils Sediments 9 (1), 62–73.

Provoost, J., Tillman, F.D., Weaver, J.W., Reijnders, L., Bronders, J., Van Keer, I., Swartjes, F., 2010. Vapour intrusion into buildings – a literature review. In: In: Daniels, J.A. (Ed.), Advances in Environmental Research, vol. 5. Nova Science Publishers, New York, pp. 1–43.

Rowe, R.K., Booker, J.R., 2004. POLLUTE©v.7 1D Pollutant Migration through a Non-homogeneous Soil. ©1983, 1990, 1994, 1997, 1998, 2004. GAEA Environmental Engineering Ltd.

Rowe, R.K., Quigley, R.M., Brachman, R.W.I., Booker, J.R., 2004. Barrier Systems for Waste Disposal Facilities, 2nd (Ed.). Spon Press, New York, USA.

Sangam, H.P., Rowe, R.K., 2001. Migration of dilute aqueous organic pollutants through HDPE geomembranes. Geotext. Geomembr. 19 (6), 329–357.

Shang, H., Cao, W., Wang, B., 2014. Effect of fast freeze-thaw cycles on mechanical properties of ordinary-air-entrained concrete. Sci. World J. 2014.

Snape, I., Harvey, P.M., Ferguson, S.H., Rayner, J.L., Revill, A.T., 2005. Investigation of evaporation and biodegradation of fuel spills in Antarctica: I - a chemical approach using GC-FID. Chemosphere 61, 1485–1494.

Snape, I., Ferguson, S.H., Harvey, P.M., Riddle, M.J., 2006. Investigation of evaporation and biodegradation of fuel spills in Antarctica: extent of natural attenuation at Casey Station. Chemosphere 63, 89–98.

Snape, I., Filler, D., Barnes, D., 2008. Contamination, regulation and remediation: an introduction to bioremediation of petroleum hydrocarbons in cold regions. In: Filler, D., Snape, I., Barnes, D. (Eds.), Bioremediation of Petroleum Hydrocarbons in Cold Regions. Cambridge University Press, Cambridge, pp. 1–37.

USEPA, 2008. Brownfields Technology Primer: Vapour Intrusion Considerations for Redevelopment. U.S. Environmental Protection Agency, Washington, DC.

USEPA, 2015. In: OSWER Technical Guide for Assessing and Mitigating the Vapor Intrusion Pathway from Subsurface Vapor Sources to Indoor Air. U.S. Environmental Protection Agency. Office of Solid Waste and Emergency Response.

Yao, Y., Shen, R., Pennell, K., Suuberg, E., 2013. A review of vapour intrusion models. Environ. Sci. Technol. 47 (6), 2457–2470.